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13. ABSTRACT

Experiments were conducted in a Link GAT-2 to evaluate the effectiveness of a system providing direct control over aircraft maneuvering performance. Pilots performed complex navigational tasks involving the use of a computer-assisted area navigation system. Changing waypoint storage capacity of the simulated navigation system induced variable task loading on subjects. The experiment was replicated with and without a self-adaptive side task to determine levels of residual attention associated with the control modifications and the varying workload levels. The flight performance controller yielded greater precision of maneuvering control, fewer procedural blunders, and an increased level of residual pilot attention. The side task proved to be a reliable discriminator of changes in workload associated with small changes in system design and task complexity.

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Sincere appreciation is expressed to Professor Stanley N. Roscoe for his encouragement and guidance in the undertaking and completion of this work.

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INTRODUCTION

Manual Control Response

Historically, the manual control response of an airplane has remained substantially unchanged. The shape and kinematic behavior of the cockpit control mechanisms have been improved, the forces required to operate the controls have been modified favorably, and some stability augmentation has been added; but there has been no systematic effort to reorganize the manual control task or to improve the dynamic relationships between manual control inputs made by the pilot and the resulting aircraft responses.

Some airplanes feature control augmentation devices which provide softly coupled automatic coordination and lift compensation in turns. However, efforts to reduce training time, improve safety, and reduce attention required for flying duties during the performance of other tasks have not included a reexamination of the most basic variables in manual control system design. Rather, efforts to improve control systems have been restricted to the refinement of handling qualities criteria for aircraft with traditional control behavior (Cooper and Harper, 1969; Gilruth, 1943; Phillips, 1949). This has resulted in the improvement of the stick or yoke and rudder pedals as devices for controlling, not the airplane directly, but rather its ailerons, elevator, and rudder -- the positions of which are of little personal interest to the pilot.

It is paradoxical that so much human engineering research effort has been devoted to display system design and so little has dealt with the contributions of bad manual control dynamics to the difficulty and danger of learning to fly. The paradox lies in the fact that improper manual control of an airplane is thought of first as a training problem, second as a display problem, and only rarely as a problem in basic control design. Nonetheless, it is an experimental fact that when instrument naive pilots fly into a cloud they wind up in a graveyard spiral within an average of three minutes (Ryan, Stonecipher, and Aron, 1954). In such cases, the spiral divergence characteristic of many aircraft combines with

the lack of an external, horizontal reference to produce a dangerous situation. It is suggested that this and countless similar examples should be treated as control dynamics problems as well as training and display problems.

In the aircraft manual control loop, there are three sets of dynamic relationships with which the pilot must deal. These relationships, depicted in Figure 1, are between (1) the movement of the airplane and the movement of the indications on the various cockpit displays, (2) the movement of the display indications and the movement of the controls, and (3) the movement of the controls and the movement of the airplane, thus completing the loop. The difficulty experienced by a pilot in dealing with these relationships depends largely upon whether they are simple, direct and invariant, or complex and variant from one flight regime to another.

Research has resulted in greatly simplified relationships of the first and second types as embodied, for example, in flight director systems and map-type horizontal situation displays with integral command guidance indications. However, little has been done to simplify the basic dynamic relationships among stick, rudder, and throttle and aircraft response despite the fact that these relationships can be extremely complex and change with the conditions of flight.

In general, depending on an airplane's configuration, the pilot's workload in maintaining control is affected by variations in gross weight, airspeed, and power, as well as aerodynamic and inertial coupling among the three aircraft axes. A thorough stability and control analysis of an airplane involves the assessment of a large number of force coefficient derivatives which represent the change in aerodynamic forces resulting from changes in airplane attitude, control deflections, and power. While the pilot is not usually aware of the subtle contribution of each force coefficient to his flight path, he is nevertheless involved with continuous coordination of the controls to achieve and maintain a desired flight condition.

In addition, in limiting flight conditions involving physical constraints or partial airflow separation on aerodynamic surfaces, large-scale changes in control

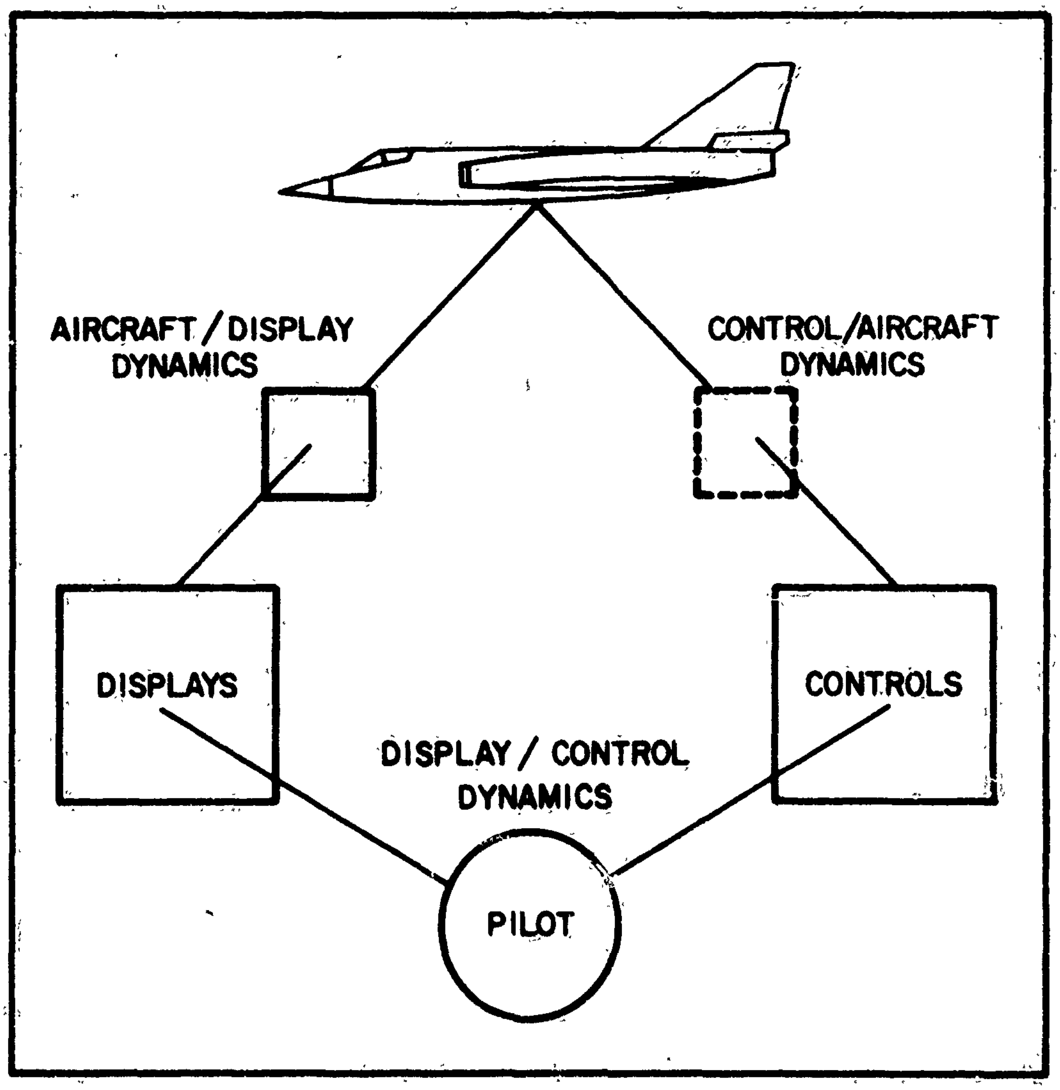


Figure 1. Diagram of aircraft manual control loop showing dynamic relationships between aircraft and displays, between displays and controls (through the pilot with his own dynamics), and between controls and aircraft, the object of this study.

behavior occur. For example, in normal flight, lateral displacement of the stick controls angular rate about the longitudinal axis of the aircraft, while the rudder pedals are used to control yaw. However, during most of the takeoff run and landing roll after touchdown, displacement of the stick has no effect on roll rate but does have an immediate and pronounced effect on yaw. Worse yet, this effect is in the opposite direction to that normally expected (that is, right stick causes left yaw). Furthermore, when the airplane is stalled, the rudder pedals become the effective control for roll.

It is evident that eliminating inconsistencies of control and establishing more direct and invariant relationships between the pilot's manual control inputs and the responses of the aircraft, without depriving him of authority over any useful maneuver, would simplify flight control and thereby allow the pilot to devote more attention to other tasks. Student pilots could learn to fly more quickly and safely, and experienced pilots could make the transition from one aircraft to another more readily.

The objective of this experiment was to evaluate a reorganized airplane control system in a complex flight mission involving area navigation. The overall performance of the modified control mode was compared to a normal control system in terms of pilotage accuracy, area navigation procedural errors, and residual attention.

Area Navigation

Aircraft radio navigation in the United States is carried out mainly by reference to ground radio facilities spaced irregularly across the country. VOR (Very high frequency Omni-directional Radio) stations provide radial bearing referenced to local magnetic north. DME (Distance Measuring Equipment) provides line of sight distance from the station to an aircraft (slant range). A TACAN (ultra high frequency TACtical Air Navigation) provides signals for determining both bearing and distance between the station and an aircraft. VORTAC stations combine the capabilities of civilian VOR and DME and military TACAN in a single facility.

These radio facilities are placed at or near busy air terminals and along the routes between them. An airplane with standard VOR and DME receivers obtains

straightforward position and guidance information only if it flies from station to station, rather than directly from its point of departure to its destination. When an airplane's course does not lead directly to or away from a ground station, the pilot must triangulate his position by reference to two VOR stations or plot radial and distance information from a VORTAC. The process is tedious in the cockpit environment and should not be attempted when the expected workload will be high.

Area navigation refers to any system of navigation that allows the use of all airspace, without restrictions associated with the geographic locations of radio navigation facilities. Recently available airborne sensing, computing, and display systems that provide area navigation (RNAV) capability are now coming into general use. Area navigation systems provide the capability of selecting any given point, called a waypoint, within the range of a VORTAC facility and flying to that point along any course with directional guidance and a continuous display of aircraft position and heading with respect to that destination.

Figure 2 shows the layout of a typical waypoint and course. For this case, assuming the VORTAC to be at O'Hare Airport, and the desired wyapoint to be at the Gary, Indiana airport, waypoint parameters are: frequency = 113.9, radial = 144°, distance = 32 nmi. The aircraft is shown flying inbound to the waypoint on a course of 30 degrees. Note that, as in navigating station to station along VOR airways, the aircraft may have to be given a crab angle relative to the course to compensate for wind drift.

A troublesome aspect of area navigation operations is that a pilot has many opportunities to make procedural errors, either of omission or commission, while selecting radio frequencies and inputing waypoint data to the computer, particularly during periods of elevated cockpit workload. Information that must be provided to the RNAV computer to set up a waypoint includes: (1) frequency of the VORTAC station to be used, (2) VOR radial along which the waypoint is situated, (3) DME distance of the waypoint from the VORTAC station, (4) selected course, and (5) scale factor of course deviation indications. Failure to enter one of the first four items, or entering an erroneous value, has the direct effect

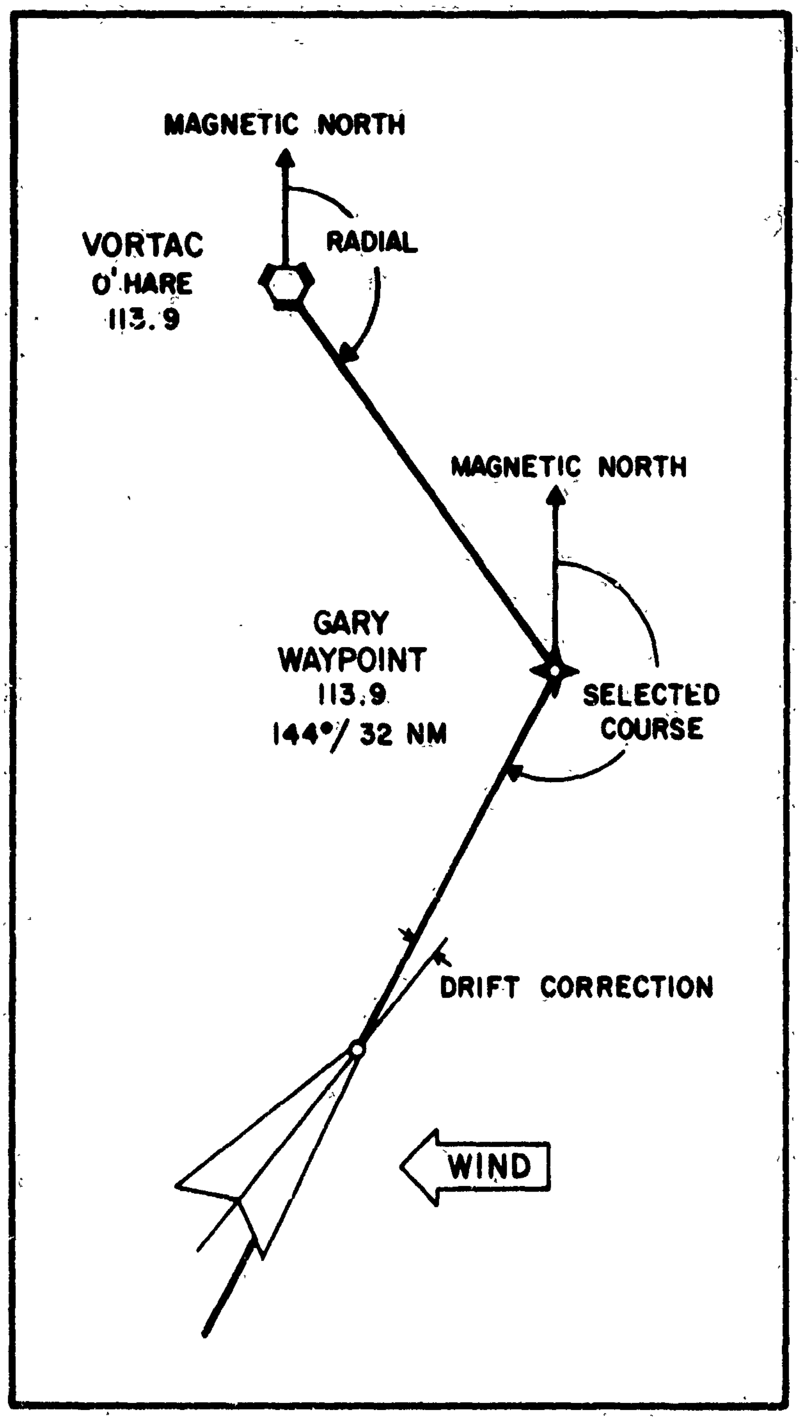


Figure 2. Layout of an area navigation waypoint showing aircraft flying along RNAV course.

of guiding the aircraft out of its assigned and protected airspace. Procedural errors of this type are commonly referred to as blunders.

It has been postulated that by providing sufficient memory in RNAV computers for simultaneous storage of several waypoints, blunders may be reduced because the pilot is able to input data during periods of reduced activity. If extra computer storage can be shown to result in fewer blunders, then a potentially serious problem in navigation safety may be avoided. The experiments reported in this study deal directly with this problem.

Residual Attention

Residual attention refers to the amount of attention a pilot has remaining for tasks in addition to his primary workload. In comparing controls or displays in simple task situations, researchers commonly find that subject pilots perform similarly on competing systems. But when overall task difficulty is increased to a level equivalent to the cockpit environment, differences in learning rates and tracking accuracies are found among the same systems. Consequently, the residual attention associated with any manual flight controller is an important basis for evaluation. Systems with a high index of residual attention allow a pilot to perform better under the stress of a high overall workload and to identify and respond to changing task priorities more quickly. Since priorities among component tasks in an overall flight situation are constantly changing, residual attention associated with cockpit workload is a time variant quantity (Damos, 1972; Damos and Roscoe, 1970).

The most accurate measure of primary task effort and, therefore, of residual attention is an overall accounting of the level of performance achieved on all tasks performed simultaneously with the primary task. This is clearly a cumbersome measure, and too task-specific to be of value in comparing systems. On the other hand, one can only approximately simulate the effects of all secondary tasks in a given situation with a single alternate task (loading task) of variable difficulty. The psychomotor interference effects of the loading task will not only

be of different form, but also will be stronger and less diverse than the multiple interference effects of the several subtasks it replaces. But while complete fidelity of the loading subtask is elusive, within a first order approximation it is enough to use any loading task that produces a realistic maximum level of overall task difficulty for all conditions of the primary task, without creating the type of interference that inverts the relative positions of any two conditions (Bahrick, Noble, and Fitts, 1954; Garvey and Taylor, 1959; Noble and Trumbo, 1967; Poulton, 1962). With regard to experiments involving system dynamics as an independent variable, inversion of conditions appears to occur only when the loading task is another continuous control task (Chernikoff, Duey, and Taylor, 1960; Chernikoff and LeMay, 1963; Duey and Chernikoff, 1960; Garvey and Taylor, 1959; Levison and Elkind, 1966; Wempe and Baty, 1968).

A good choice, then, for a secondary task to be used with a primary continuous control task is a discrete, quantifiable task, such as an information processing task using a lightboard stimulus and a keyboard response. Information theory is useful for studies involving stimulus-response loading tasks because pilot workload on the loading task, measured in terms of reaction time, increases monotonically, almost linearly, with the number of bits or bits/sec processed on the task. More importantly, in comparing condition means within simple experiments where all subtasks are similar in nature, the individual components of overall workload, in bits, may be assumed to combine additively (Hyman, 1953). Furthermore, if the workload components of a situation are known, the combined mean for the condition can be closely predicted. On this basis, subtask and overall task difficulties have been quantified in complex flight situations (Bergeron, 1968; Ekstrom, 1962).

However, some studies have found that in more complex tasks, subjects achieved a combined information processing score that was higher than was possible with either of the subtasks performed alone (Herman, 1965; Licklider, Stevens, and Hayes, 1954). Other studies have found the combined score to be lower than that for just one of the tasks (Keele, 1967; Pierce and Karlin, 1957; Wempe and Baty,

1968). Consequently, several researchers have suggested alternate schemes for obtaining overall workload from scores on the subtasks, including use of the geometric mean and the sum of the square of individual scores (Taylor, Lindsay, and Forbes, 1967; Woodworth, 1938). These techniques appear to have an advantage over the procedure devised by Hyman when the overall task is diverse. Given a situation in which it is possible to describe each of the independent mechanisms of psychomotor processing required in a given task, a promising model of the subtasks would be in the form of two vector sets, an orthogonal set for non-interfering tasks and a nonorthogonal set for tasks with overlapping components. The vector sum of all subtask vectors would contain each total component of the overall psychomotor process, and would represent workload in basic terms. The analogy can be continued further to the vector cross product for describing two independent stimuli which combine during mental processing to direct attention in a third independent direction. In addition, if the combination schemes of Woodworth (1938) and Taylor et al. (1967) are correct for simultaneous performance of diverse subtasks, as they appear to be, then it is possible that subtasks combine as vector products. The vector model of workload bears further study, but would require considerable calibration before it could become a useful quantifying technique.

While difficulties exist in interpreting side-task scores in terms of total human capacity for information processing, or even in terms of overall workload, a properly designed side task is capable of giving a useful indication of residual attention. By developing a standardized side task that produces a minimum of psychomotor interference with a set of primary tasks, competing devices may at least be compared to a common standard (Knowles, 1963).

Side tasks are classified as either self-adaptive or cross-adaptive. The rate of activity on a self-adaptive task varies as a function of the subject's performance on the side task itself, whereas the workload presented by a cross-adaptive task is a function of performance on the primary task. The use of self-adapting side tasks casts variability into both primary and secondary task performance because neither task workload is actively controlled. By controlling performance on the primary task, through the use of a cross-adaptive secondary task, it is possible

to obtain a curve of primary task performance versus residual information processing capacity. However, this technique is not adaptable to a complex flight task because the performance measures for all subtasks do not reduce rationally into a single cross-adapting performance variable. Thus faced with the problem of "adding apples and oranges," the experimenter turns to self-adaptive or self-pacing side tasks.

Carefully instructing subjects on the relative attention to devote to primary and secondary tasks can be of help in minimizing variability when self-adaptive tasks are used (Triggs, 1968). A common instruction is to have subjects give equal attention to both primary and secondary tasks. But, Geissler (1909) points out that this instruction is very difficult to follow, especially when the tasks are considerably different, and it is likely that each subject's perception of subtle cues in the experiment will affect his individual attention sharing (Triggs, 1968). Consequently, subjects should be instructed to give primary attention to one of the tasks.

APPROACH

Control Authority

A good starting point in approaching any system design problem is first to determine the functions the system must perform to accomplish its given mission and then the best distribution of those functions between the people in the system and automatic mechanisms. The fixed-wing aircraft has six degrees of freedom or maneuverability, three translational and three rotational, and the control of these constitutes the functions to be performed. Thus the first research task is to decide on a basis for distributing control authority and responsibility for these functions between the pilot and the automated portions of the control system.

At least in theory, it would be possible to provide means of control that would give the pilot authority over position, rate, acceleration, or rate of change of acceleration with respect to any or all of the six degrees of freedom. The further along this list his authority extends, the more complete and direct his control over the aircraft and its subsystems, but by the same token the greater his responsibility for coordinating moment-to-moment control inputs. As his control authority shifts in the opposite direction, the system becomes increasingly automatic, his direct control responsibilities diminish, and the system tends to lose real-time flexibility.

The essential problem appears to be that of determining the point at which the pilot should interface with semiautomatic controls to minimize the difficulty of his control task without depriving him of the minimum essential control authority to counter any reasonably likely flight contingency. To the extent that he can be removed from the inner loops of control, where he performs integrating and coordinating functions for virtually every subsystem of the airplane, he will be unburdened of the routine of repetitive manipulation and his performance will be more precise and less variable (Birmingham and Taylor, 1954; Kelley, 1968).

Considering the requirements for both simplicity and flexibility of control, it is apparent that the region of experimental interest with respect to the three

degrees of translational freedom lies somewhere between rate control and acceleration control for the pilot. Clearly, direct manual control of rate of change of acceleration would appear to be unnecessarily difficult and of no useful purpose. In the case of rotational freedom, position control makes a great deal of sense as does rate control, while acceleration and rate of change of acceleration control become increasingly difficult.

Experimental Studies

Airplane control dynamic response characteristics have remained basically unchanged for decades because the overriding requirement for reliability dictated the use of direct mechanical links from the pilot to each control surface. Until very recently, even the hydraulic augmentation systems employed in large and fast aircraft have been parallel installations, providing basically identical dynamic responses to manual control inputs that unboosted controls provide. With modern electronic hardware reliability approaching airframe reliability, "fly-by-wire" systems providing modified flight dynamic behavior are becoming realistic, and some designers now support the concept of "control configured" vehicles.

Work has been in progress for several years to improve the dynamic response of helicopters through the use of fly-by-wire systems (Walchli, 1970), and a similar approach has been taken with fixed-wing airplanes by Loschke, Barber, Jarvis, and Enevoldson (1972) at the NASA Flight Research Center.

The NASA group used a light, twin-engined airplane to evaluate two augmented control modes relative to normal control behavior on ILS approaches. The modified modes allowed either pitch or roll rate control with a yaw damper or pitch and roll attitude control with a yaw damper and heading hold. Two NASA test pilots made flights under varying levels of atmospheric turbulence and showed that glideslope and localizer errors were significantly reduced when using attitude command with yaw damping and heading hold. Cooper ratings (Cooper and Harper, 1969) for both attitude and rate commands were higher than for normal control, with the attitude command rating being far superior.

These efforts represent a good starting point in the exploration of modified control dynamics. With the large variety of possible flight tasks and conceivably superior control modes, there still remains a multitude of opportunities for continued experimentation, particularly with regard to questions of cockpit workload as well as tracking accuracy.

METHOD

Before beginning the experimental evaluation of a reorganized manual control system for airplanes, an initial investigation was conducted to outline aircraft control functional requirements for a broad range of flight missions and to define several promising categories of control dynamic behavior. Four control dynamic modifications, including vertical speed command, bank angle command, sideslip angle command, and follow-up (automatic) trim were implemented individually and in 11 combinations in a Link GAT-2 ground-based general aviation trainer. The GAT-2 has been extensively modified to provide variable stability and variable control feel and is coupled with a Raytheon 704 digital computer for simulation of complex navigation tasks. In addition, a self-adaptive discrete information processing secondary task generator was integrated with the GAT-2 to achieve limiting levels of pilot workload and to measure residual attention.

Preliminary Experimentation

An initial experiment, involving 16 instrument-rated pilots performing continuously maneuvering flight in accordance with a memorized, time-referenced pattern, measured the effectiveness of three dynamic modifications: vertical speed command for "pitch" control, bank attitude command for "roll" control, and yaw damping to provide automatic coordination. The experiment showed that pilots retained all essential flexibility of control with the individual dynamic response modes and that when all modifications were implemented simultaneously in what has been termed a maneuvering performance control system, precision of maneuvering was increased and pilot workload was reduced. Both effects were statistically reliable.

Experimental Tasks

Primary Task. The evaluation of control dynamic modifications not only must include speed and precision of basic aircraft maneuvering but also must

consider indirect effects on procedural compliance and pilot workload. Thus the experimental situation was designed to include the automated measurement of a pilot's residual attention, as well as tracking accuracy, while performing computer-assisted area navigation tasks of a highly demanding procedural nature.

One means of reducing procedural errors associated with navigation computer inputting is to provide capacity for simultaneous storage of several waypoints, thereby allowing the pilot to set up all or part of his flight plan either before takeoff or during periods of low workload enroute. Consequently, waypoint storage capacity (1, 2, 4, or 8) was included as an independent experimental variable, and the number of procedural blunders made by pilots was taken as a dependent variable.

The effects of the number of waypoints available in storage and of manual flight control dynamics (normal versus performance control) on procedural blunders and tracking accuracy were compared both with and without a side-task induced elevation of pilot workload.

Secondary Task. In the first of two replications of the experiment, total workload for each pilot was held at his maximum momentary capacity by the introduction of a self-adaptive information processing task in which the information input increased or reduced automatically as the pilot's performance on the secondary task improved or deteriorated. The secondary task served as both an independent and dependent variable, thereby allowing observation of the effect of varying secondary workload on errors in navigation and control, while at the same time giving an index of the relative effort required for each of the experimental conditions. This unique dual role for the secondary task required that special attention be given to the choice and tuning of all side-task parameters.

In these experiments, the primary task involved aircraft control, and the subject pilots were instructed to give primary attention to the control task. A reminder horn was added, however, to assure that pilots would keep the side task in mind. The horn sounded if the pilot failed to respond correctly to a new

stimulus within a given length of time. It may be expected that the reminder horn would cause pilots to invert the importance of the two tasks. This was avoided, however, by proper timing of both the response/new-stimulus interval and the stimulus/reminder-horn interval. Pilots were able to ignore the horn when the momentary loading of the primary task was high, and on the whole, treated the side task as they would treat a call from the tower while making a difficult instrument approach to a landing -- attend to it only when it would not degrade performance to an unacceptable level.

Time intervals between the side-task functions are very important. Experience during preliminary testing indicated that pilots become extremely frustrated when the stimulus/reminder-horn interval is shorter than four seconds because they do not have sufficient time to complete an instrument scan and make necessary corrective flight control actions between responses. In experiments of extended length, this frustration turns to hostility in some subjects. The minimum acceptable horn delay time depends largely upon primary task difficulty and the proficiency of the pilot subjects. It is desirable to have the shortest interval that is tolerable to optimize experimental sensitivity, but the experimenter must allow the subjects sufficient time to navigate and fly the airplane. Otherwise pilots will not only become frustrated but their performance will become highly variable, first reflecting loss of normal command followed by a state of panic. The reminder horn becomes a severe stressor if not carefully timed.

In these experiments, the stimulus/reminder-horn interval was set so that, in the most difficult combination of experimental flight conditions, a current instrument-rated pilot who attempted to make all the responses within the horn delay time would most likely lose control. A stimulus/reminder-horn interval of six seconds was chosen and worked very well.

The 0.75-second interval between a correct response and the presentation of a new numerical stimulus was chosen to avoid having the pilot give primary attention

to the side task. In pretesting, a correct response followed immediately by a new stimulus proved to be too distracting. Pilots tended to invert the relative importance of the flight task and side task. One pilot eventually became frustrated with the insatiable demands of the side task and tended to ignore it. On the other hand, a long delay between correct response and new stimulus caused pilots to lose their state of readiness for side-task stimuli and forget about the side task until the horn sounded. The response/new-stimulus interval must therefore be neither so short that it inverts the importance of tasks or causes frustration, nor so long that it is forgotten. The 0.75-second interval was successful in keeping priorities in line.

GAT-2/Raytheon 704 Simulation Facility

GAT-2. The Link GAT-2, shown in Figure 3, is a twin-engined general aviation trainer built by the Singer Corporation to provide ground training for instrument flight conditions in light, twin propeller-driven airplanes. The overall cockpit layout, Figure 4, follows that of Cessna 400 series aircraft, and includes yoke, rudder pedals, power control pedestal, and instrument panel subassemblies from the Cessna 421. Motion simulation is provided by hydraulic actuators for both pitch and roll. The cockpit attitude at any moment is linearly scaled from the true flight values of pitch angle and bank angle. The flight equations for which the trainer's self-contained analog computer is designed are based upon the characteristics of the Beechcraft Baron and Cessna 310, although some approximations were made by Link in the simulation of control feel and second order aerodynamic effects. Considerable attention was given to modifications and additions to the analog computer to assure that the GAT-2 flight behavior was representative of light, twin-engined airplanes (Stoddart, 1971).

Navigation in the basic GAT-2 is with reference to a flat, finite world that is 172.6 miles square. Navigational aids including ILS, marker beacon, commercial radio, and VOR/DME stations may be positioned at will on this surface, so that any desired region can be simulated.

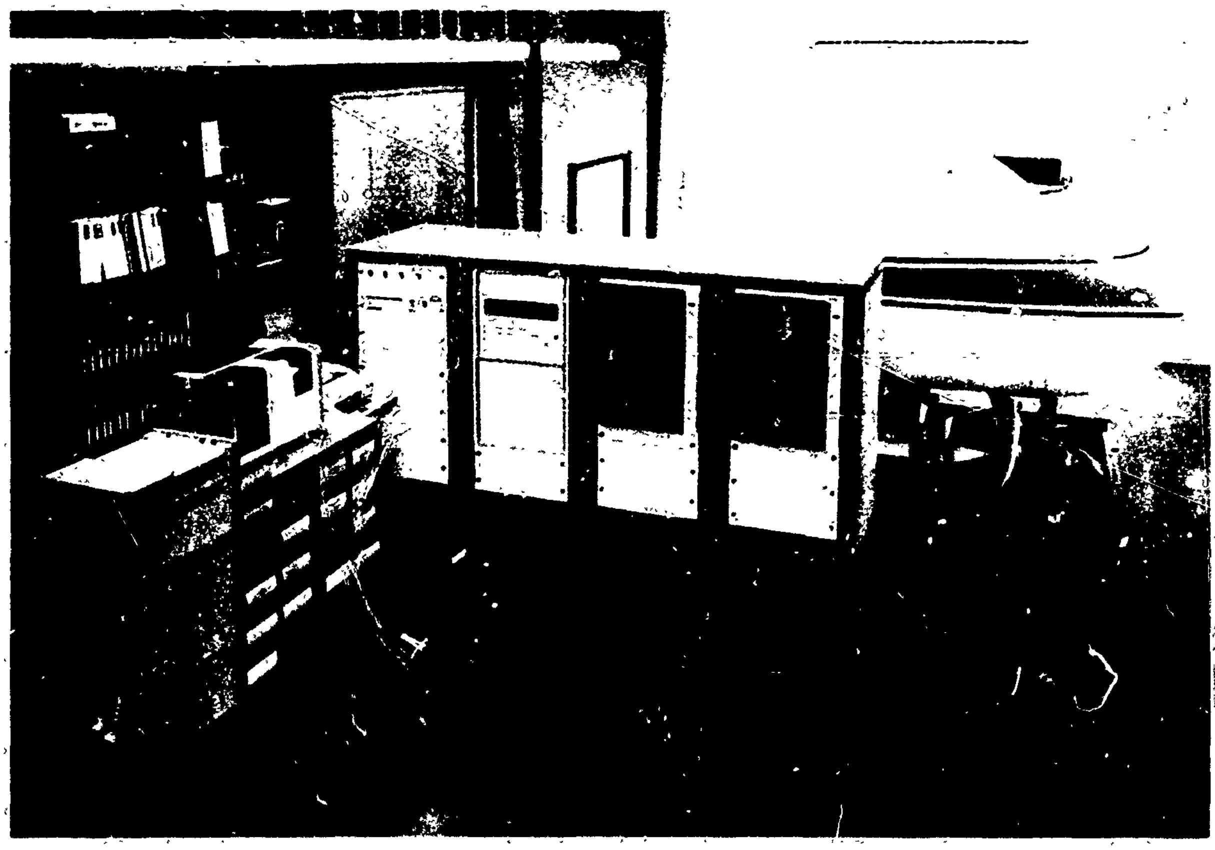


Figure 3. Aviation Research Laboratory's flight simulation facility, including a Raytheon 704 high-speed minicomputer interfaced with a highly modified Link GAT-2 general aviation trainer.

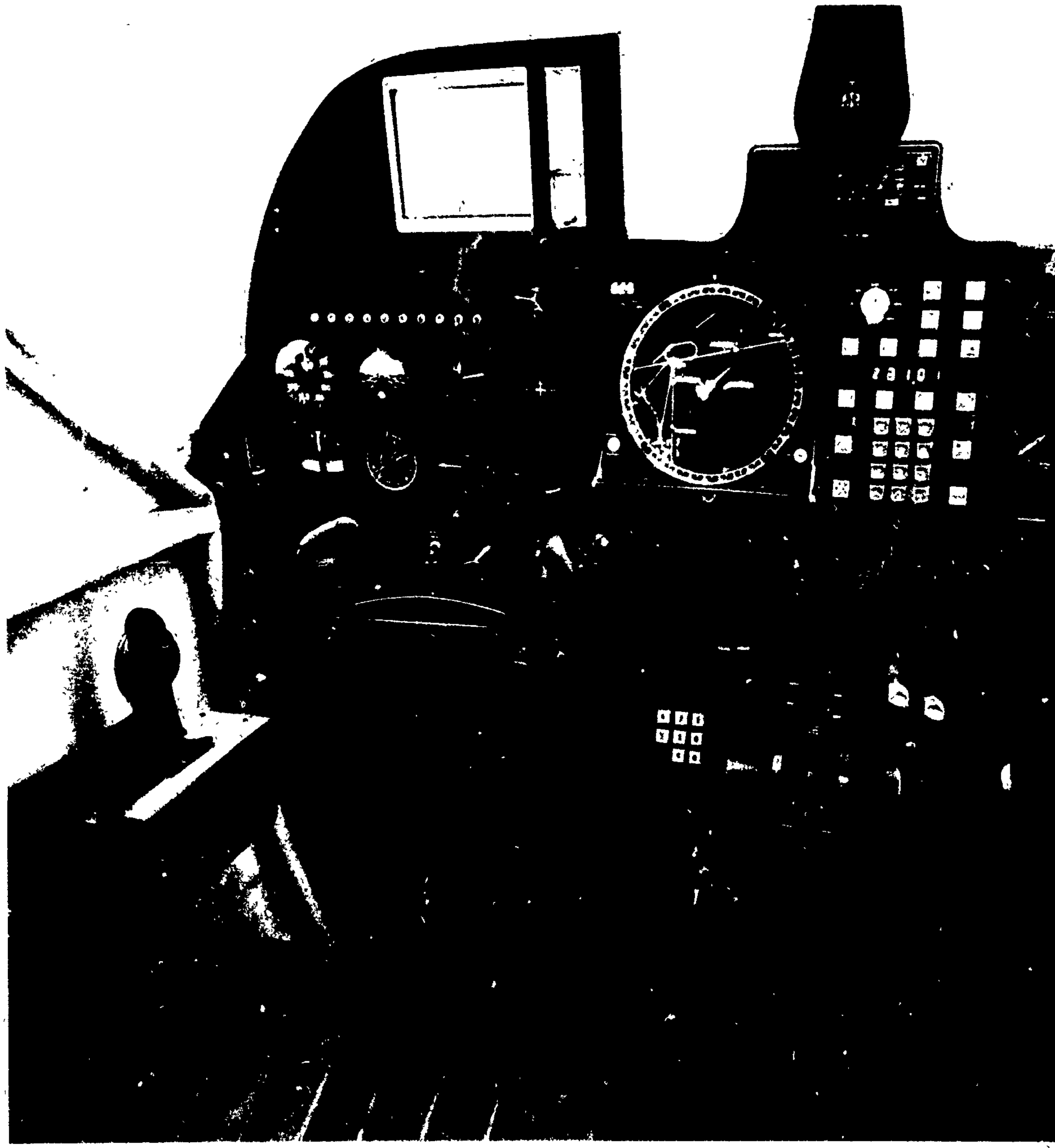


Figure 4. Link GAT-2 modified cockpit interior, including sidearm flight controller, digital keyboard control-display unit (CDU), Hughes Navigation Director optically projected map display (not used in this experiment), and horizontal numeral array (above main flight instruments) and scrambled keyboard (near pilot's right kneewell) used in measuring residual attention. The Butler Symbolic Pictorial Indicator (SPI) used as the primary area navigation display is included in the main instrument flight group.

Sidearm Controller. Early experience with control dynamic modifications in the GAT-2 showed the desirability of separating the effects of control response and control force feedback. For this reason, a sidearm stick controller was mounted on the pilot's left armrest (Figures 4 and 5) and was used for both normal and modified control on all flights. The controller can be rotated about all three axes, thereby combining the capabilities of both stick and rudder in one mechanism. Control forces are provided by preset centering springs in the linkage, and therefore do not vary with indicated airspeed or attitude.

Standard trim controls for the three aircraft axes are provided on the power pedestal. The trim controls vary the electrical null position of each of the three stick axes, thereby providing offsets that allow the pilot to trim the aircraft for any condition he desires. Because the spring centering forces within the stick are simply a linear function of stick position, control forces remain unchanged with trim changes.

Raytheon 704. The Raytheon 704 digital computer (Figure 3) extends the navigational capabilities of the GAT-2 to include area navigation by simulating the functions of an airborne area navigation computer. As shown in Figure 6, the digital computer receives position information from the GAT-2 computer and navigational command inputs from the cockpit control-display unit and returns course errors to the RNAV displays in the GAT-2 panel. Also, the Raytheon computer makes the necessary computations to provide variations in RNAV control and display parameters, such as waypoint storage capacity and display scale factors. Data regarding display variables, GAT-2 position, and tracking errors are recorded on magnetic tape for later analysis. The RNAV program allows data to be collected at selectable time intervals (.01 to 99.99 seconds). A five-second interval was chosen for these experiments.

A block diagram of the Raytheon 704 computer as a stand-alone system is shown in Figure 7 and indicates available input-output capabilities for interfacing with experimental equipment. During testing the Raytheon system included a teletype, a card reader, two magnetic tape units, 16 analog-to-digital conversion

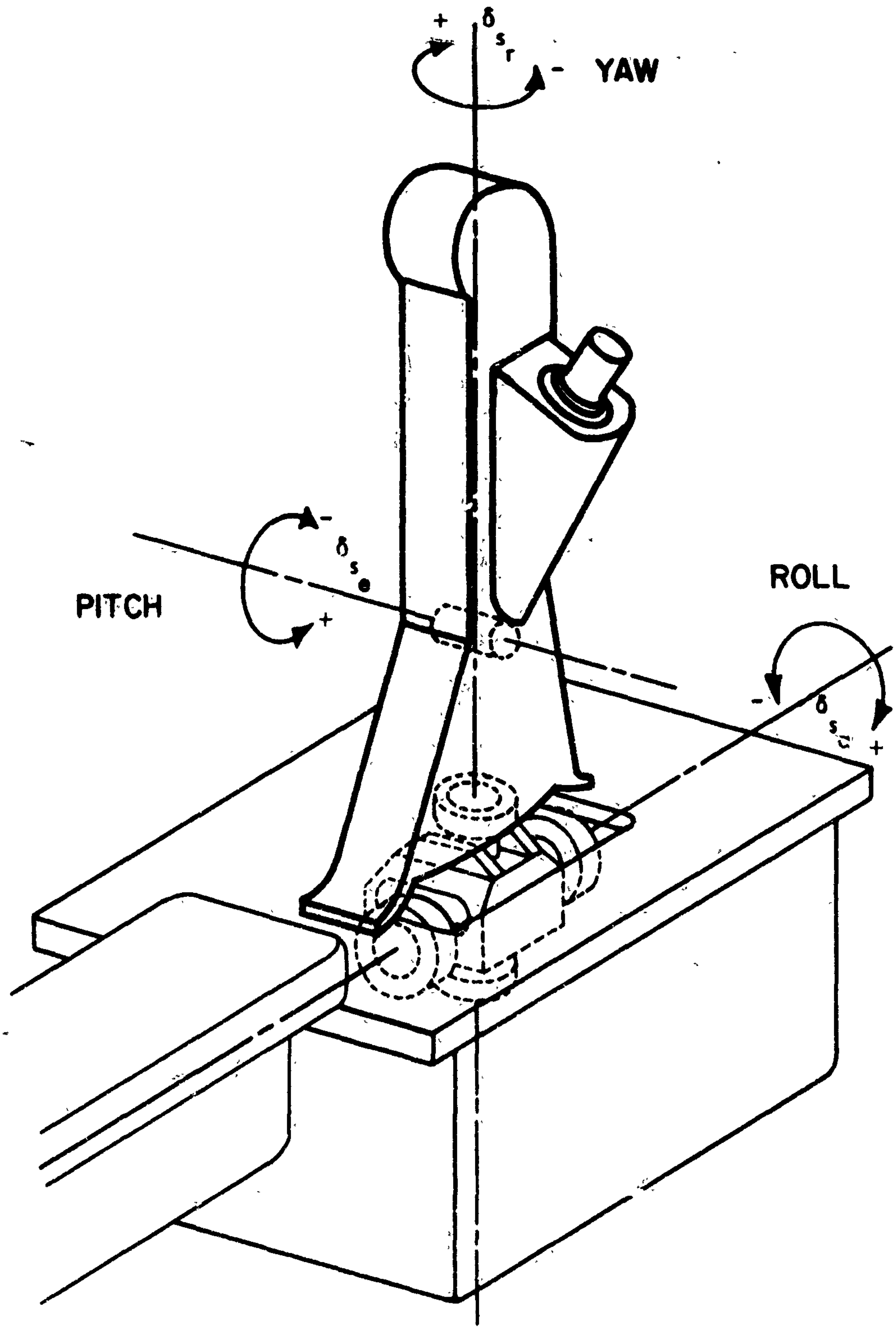


Figure 5. Three-axis sidearm stick controller mounted on the pilot's left armrest. Dotted lines show outline of portions of internal mechanism. Pitch axis is located above the base of the stick. Pushbutton on thumbrest was not used.

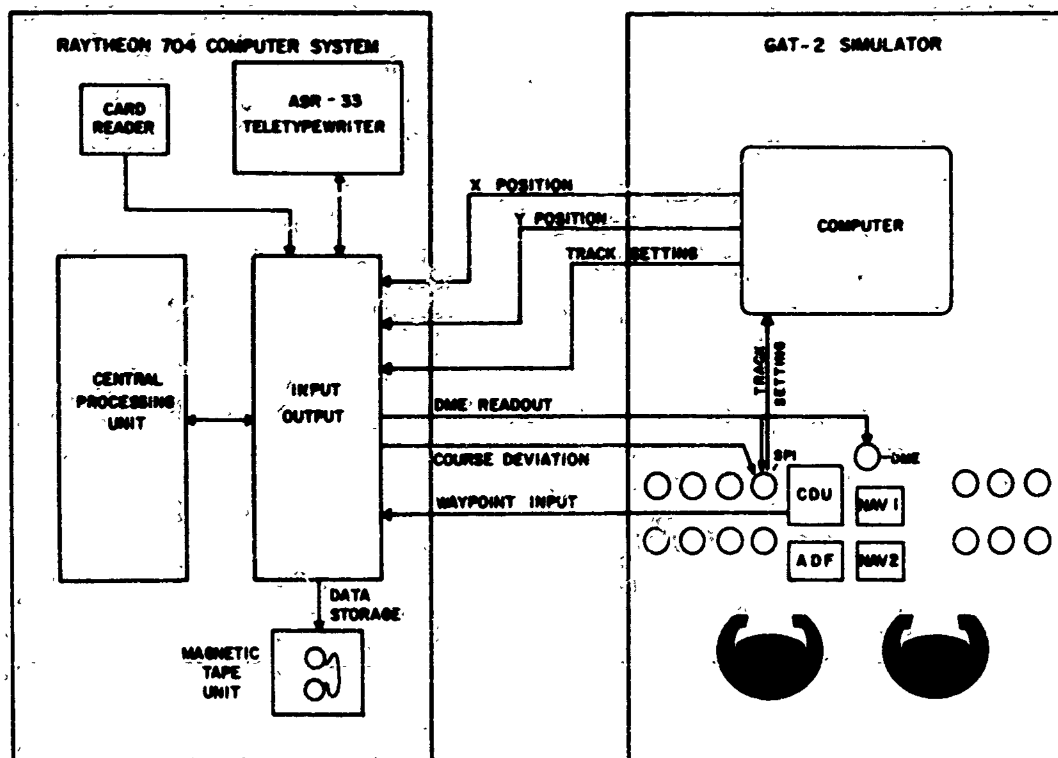


Figure 6. Functional block diagram of Link GAT-2/Raytheon 704 area navigation system.

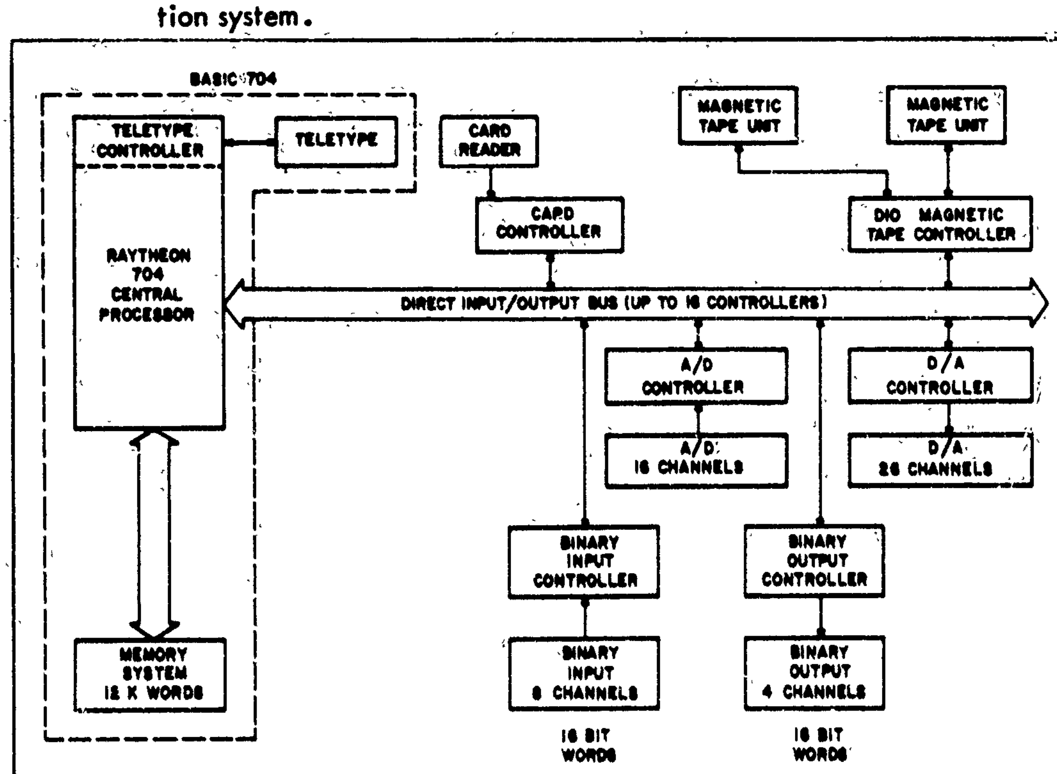


Figure 7. Raytheon 704 computer system showing input-output capability for interfacing with experimental systems.

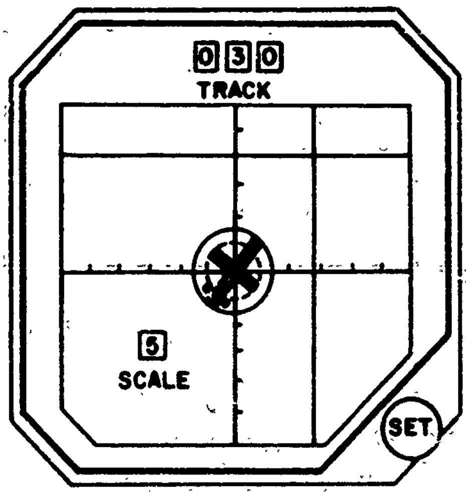
channels, 26 digital-to-analog conversion channels, four binary output channels, and eight binary input channels. Since that time, additional peripheral equipment and input-output channels have been added.

RNAV Control and Display. The primary area navigation display used in these experiments was the Butler National symbolic pictorial indicator (SPI) shown in Figure 4 and again in Figure 8. This instrument provides both position and guidance information. The desired course to or from a waypoint is selected with the SET knob and is shown in the TRACK window. The intersection of the vertical (course) and horizontal (distance) crosspointers shows the position of the selected waypoint relative to the symbolic aircraft. The angular orientation of the aircraft symbol shows heading relative to the selected course. Hashmarks on the face of the SPI indicate crosscourse and alongcourse distance increments. The window number in the lower left quadrant of the SPI indicates the scale for the hashmarks in tenths of a nautical mile. The scale factor was 0.5 nmi for the entire experiment, so that the face of the SPI represents an area five miles across in both directions.

Additional distance information is provided by a digital display positioned to the left of the control yoke. This display indicates distance in nautical miles from the simulated aircraft position to the waypoint in use, and is particularly useful to the pilot for planning his cockpit procedures when the SPI horizontal crosspointer is out of range.

The pilot selects the position of a waypoint by means of the cockpit control-display unit (CDU) which appears in Figures 4 and 8. This control-display unit is typical of those used in airborne computer-assisted area navigation systems and is used for computer entry and readout of waypoint data.

A waypoint is a reference position along the intended flight path, and is defined in terms of the frequency of a nearby VORTAC station and polar coordinates from the station to the waypoint. Up to 20 waypoints can be stored by the Raytheon 704. Frequency, radial, and distance are entered by pressing the waypoint-set (SET) button, entering a number from one to 20 to identify the



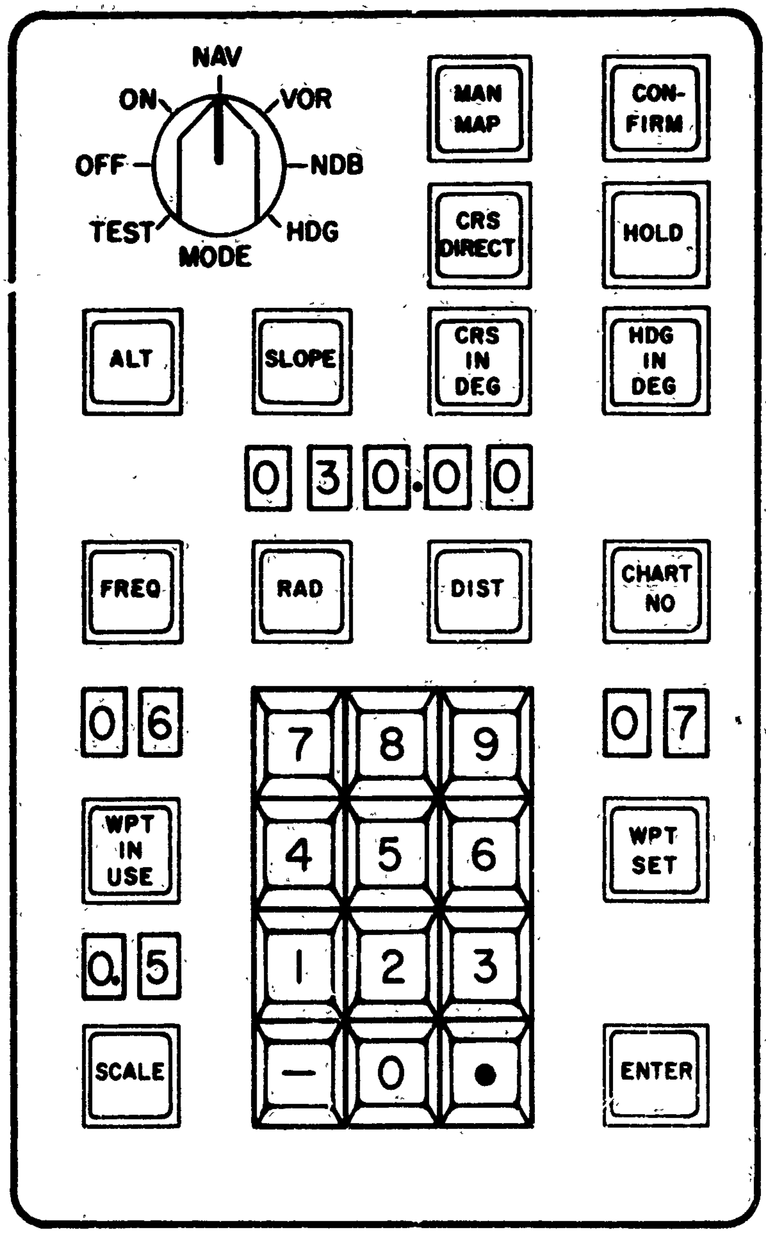


Figure 8. Butler National Symbolic Pictorial Indicator (left) and experimental area navigation control-display unit (right).

waypoint, then entering the three values. Guidance information to any waypoint can be recalled by pressing the waypoint-in-use (WPT IN USE) button and entering the number assigned to the desired waypoint. The scale of the SPI is also set on the control-display unit. Allowable scale factors range from .01 to 99 nautical miles per division.

A more complete functional description of the use of the control-display unit is given in the Instructions to Pilots, Appendix A.

Secondary Task Generator. Portions of a Massey-Dickinson digital logic system were assembled to drive an auxiliary task device. This digitally controlled self-pacing discrete side-task generator activates a linear array of transilluminated numerals, 0 through 9, mounted horizontally above the primary flight group on the pilot's instrument panel (Figure 4). Numerals 1 through 8 are illuminated in a random sequence, and as each appears the pilot can extinguish it by pressing the corresponding numeral on a scrambled keyboard mounted above his right knee and out of his normal field of view.

The keyboard is scrambled so that subjects familiar with standard calculator or telephone keyboards have no strong advantage or disadvantage due to a regular ordering of the numerals. Unused keys at the bottom of the keyboard are masked. The keyboard utilizes a lockout linkage to prevent the depression of more than one key at a time. Responses were recorded on strip charts. A block diagram of the secondary task generator appears in Figure 9.

During operation, when a pilot extinguishes an illuminated numeral, another appears after a constant 0.75-second delay. The amount of information (in bits) conveyed by the correct response to a given stimulus is defined as the logarithm to the base 2 of the reciprocal of the probability that this given stimulus will occur. With eight equally probable stimuli, each numeral correctly processed represents three bits ($\log_2 \frac{1}{1/8}$) of information (Hyman, 1953). Thus, if the pilot were to respond to every light stimulus with no delay, he would be processing a theoretical maximum of four bits of information per second. However, if a pilot fails to respond within six seconds, or responds incorrectly, the stall warning horn

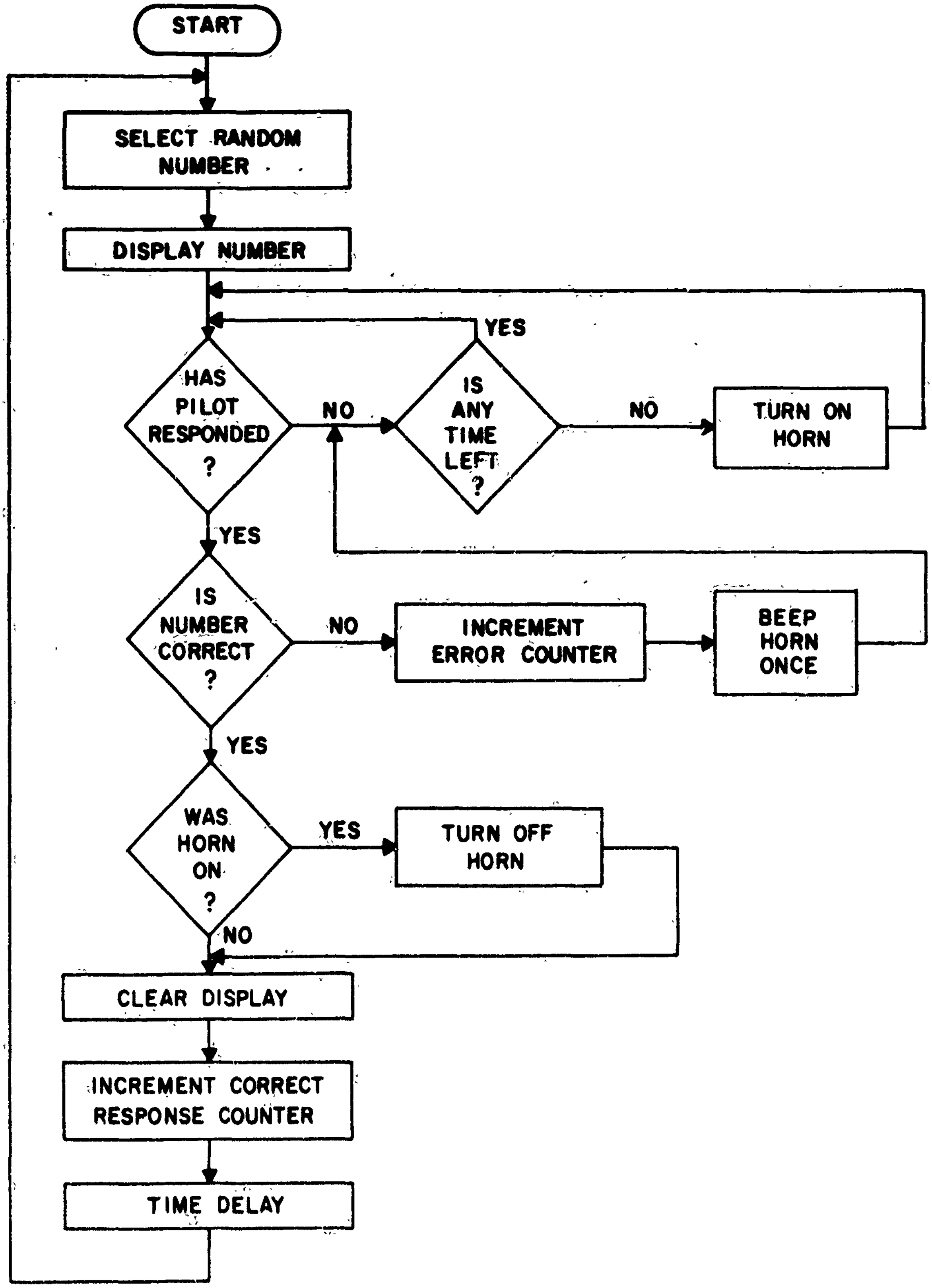


Figure 9. Functional diagram of discrete information side-task generator.

starts sounding with rapid intermittence (two evenly-spaced 250-millisecond beeps per second). The horn serves to remind the pilot to attend to the side task and to notify him of incorrect responses.

Control Modes

Two modes of control were implemented through the sidearm stick:

Normal Control. GAT-2 simulated aircraft dynamics represent those typical of a twin-engined light aircraft. Ailerons are controlled by lateral motion as with a conventional flight stick or yoke. Stick motion for pitch control is unique in that the center of rotation of the mechanism is in the palm of the hand, rather than below. Thus, elevator control is achieved with a twist of the wrist and requires no arm motion. The rudder is controlled by twisting the stick about its vertical axis rather than by pushing rudder pedals.

Performance Control. "Fore and aft" rotation of the stick controls vertical speed rather than pitch attitude, with the neutral detent position calling for level flight unless trimmed otherwise. In turns, additional elevator deflection is automatically applied to compensate for reduced vertical lift due to banking. Lateral rotation of the stick controls bank angle, and therefore turn rate rather than roll rate, with the spring-centered detent position calling for a wings-level attitude. No manual control of yaw is required for coordinated turns; rotation of the stick about its vertical axis is required only to produce a sideslip in a banked attitude to compensate for wind drift.

Figure 10 compares the vertical rate response of the GAT-2 to fore and aft stick inputs with normal and performance control modes. In the normal control mode, the vertical speed fails to reach a steady value with the stick fixed in any position. In climbs, decreasing airspeed and phugoid-like behavior combine to make it very difficult to attain and hold a constant vertical rate. With the stick forward, the rate of descent is also affected by longitudinal dynamics and gradually increases with increasing airspeed. In the performance control mode, the vertical rate reaches the command value quickly with little overshoot and remains at that

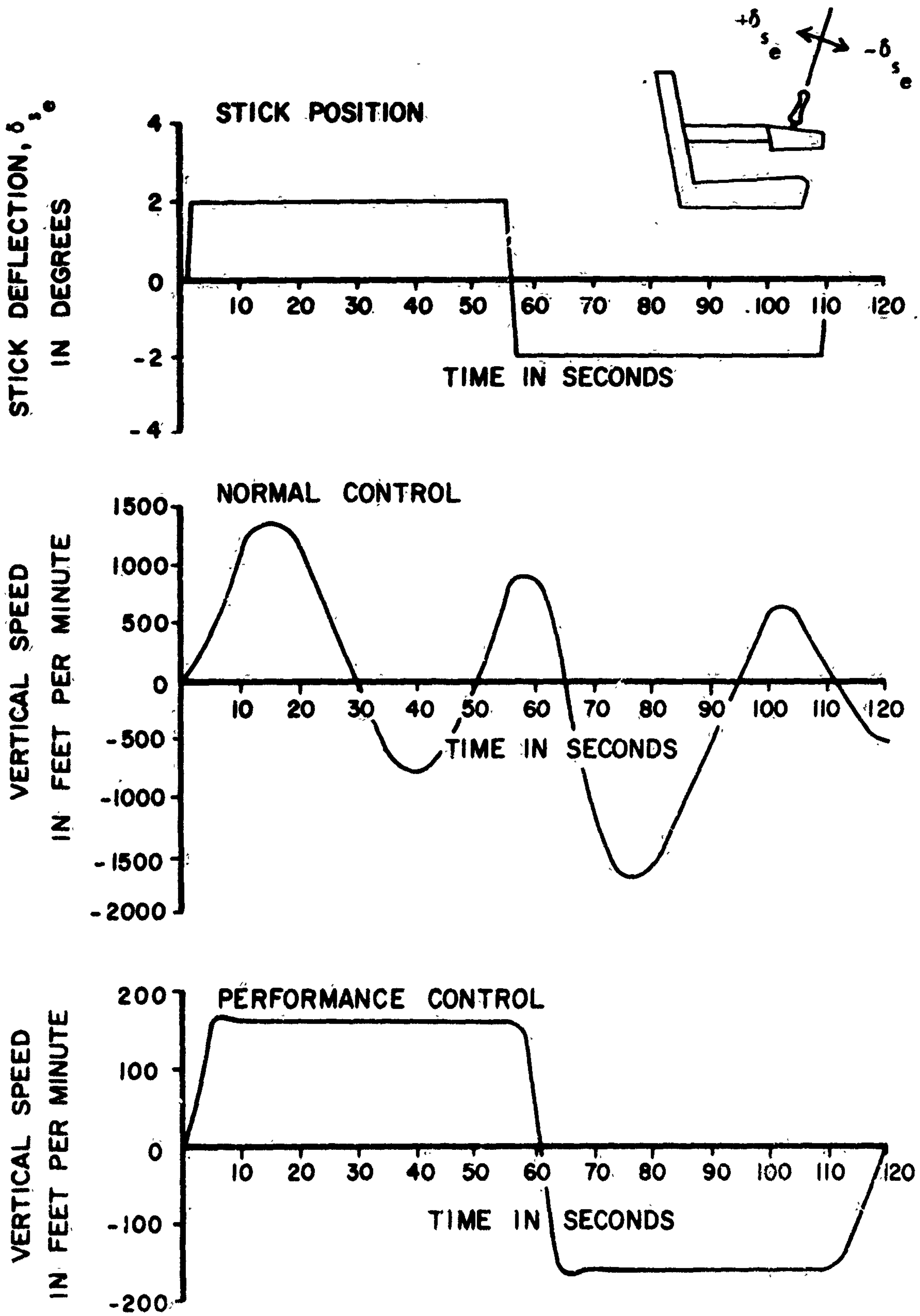


Figure 10. Comparison of GAT-2 vertical speed response to fore and aft stick inputs with normal and performance controllers. Flight parameters are: indicated airspeed, 180 knots; altitude, 3000 feet; no turbulence.

value until the stick is moved to a new position. Longitudinal dynamics are damped and the elevator is automatically coordinated with changes in airspeed. However, the performance control system will not allow the aircraft to stall unless the power is off. Power management remains the responsibility of the pilot.

Figure 11 shows the characteristics of the two modes in roll. When the stick is moved to the side, normal control gives a steady increase in bank angle. When the stick is returned, the bank angle increases a few degrees until aerodynamic damping overcomes roll inertia. The bank angle then increases slowly, and if uncorrected will lead the airplane into an ever-tightening descending spiral. This behavior is called spiral divergence, and is due to such factors as unsymmetrical thrust, slight roll trim asymmetry (due to loading imbalance, control friction, or improper trim setting), or genuine aerodynamic spiral instability. With performance control, these conditions are automatically compensated and the bank angle is stabilized at any command value.

Sideslip characteristics for the two modes are compared in Figure 12. Without rudder coordination, there is significant adverse yaw when ailerons are deflected. The performance controller provides automatic sideslip compensation. It should be noted that the nature of the GAT-2 simulation of turbulence and motion caused the performance control system to behave as if it included a yaw rate damper and heading hold capability.

The limits of motion and scale factors for each of the three stick axes are given in Table 1. Scale factors for both control modes were initially chosen to permit complete control authority for the experimental flight task and were adjusted to conform to handling qualities requirements determined by means of a pilot opinion survey. The four pilots involved in the survey were instrument and multiengine-rated pilots at the University of Illinois Aviation Research Laboratory. An important result of the survey was the addition of nonlinear control of climb and descent. As stick position, δ_{s_e}, passes through 10 degrees in either direction,

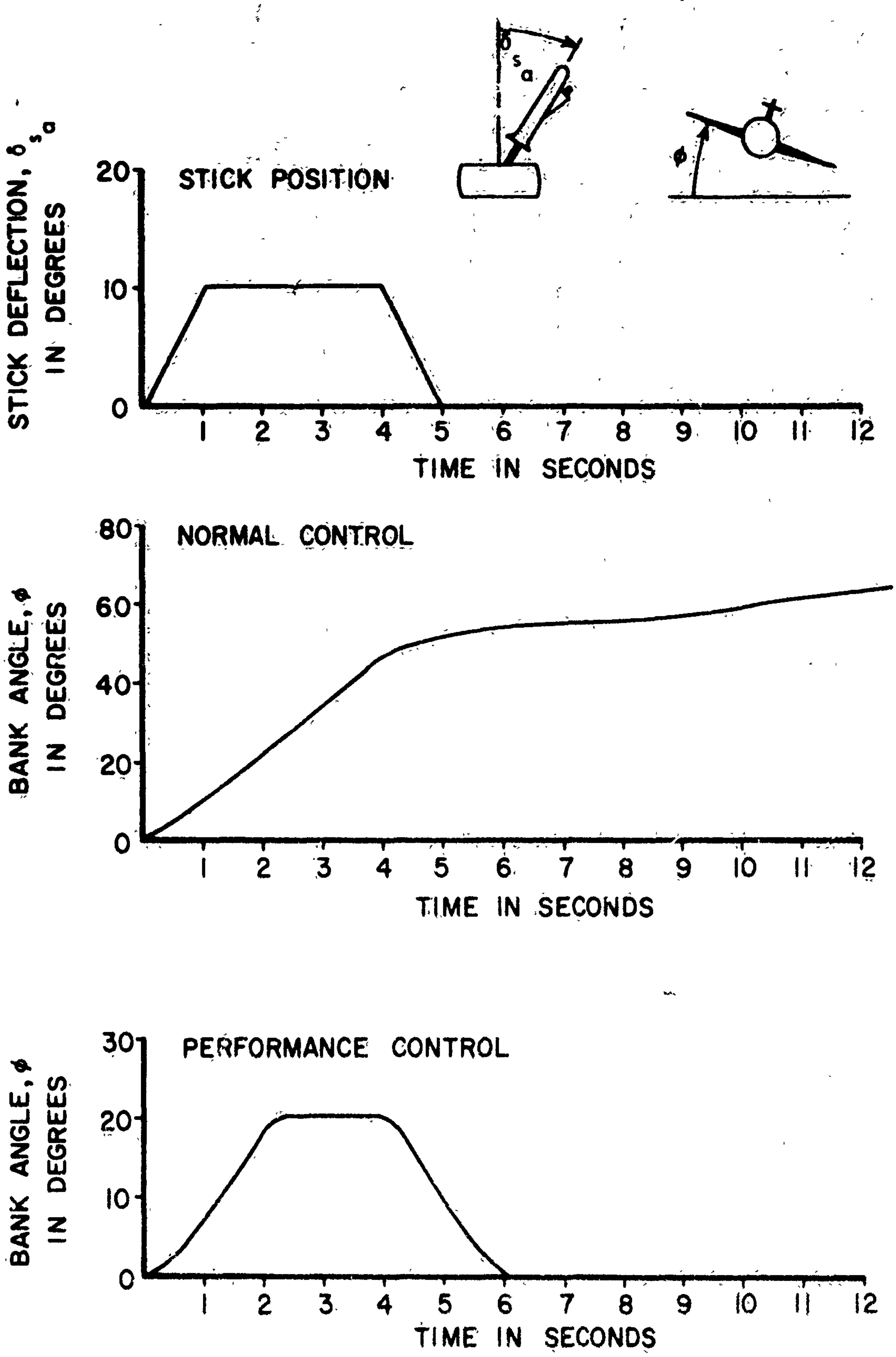


Figure 11. Comparison of GAT-2 roll response to lateral stick inputs with normal and performance controllers. Flight parameters are: indicated airspeed, 100 knots; altitude, 3000 feet; no turbulence.

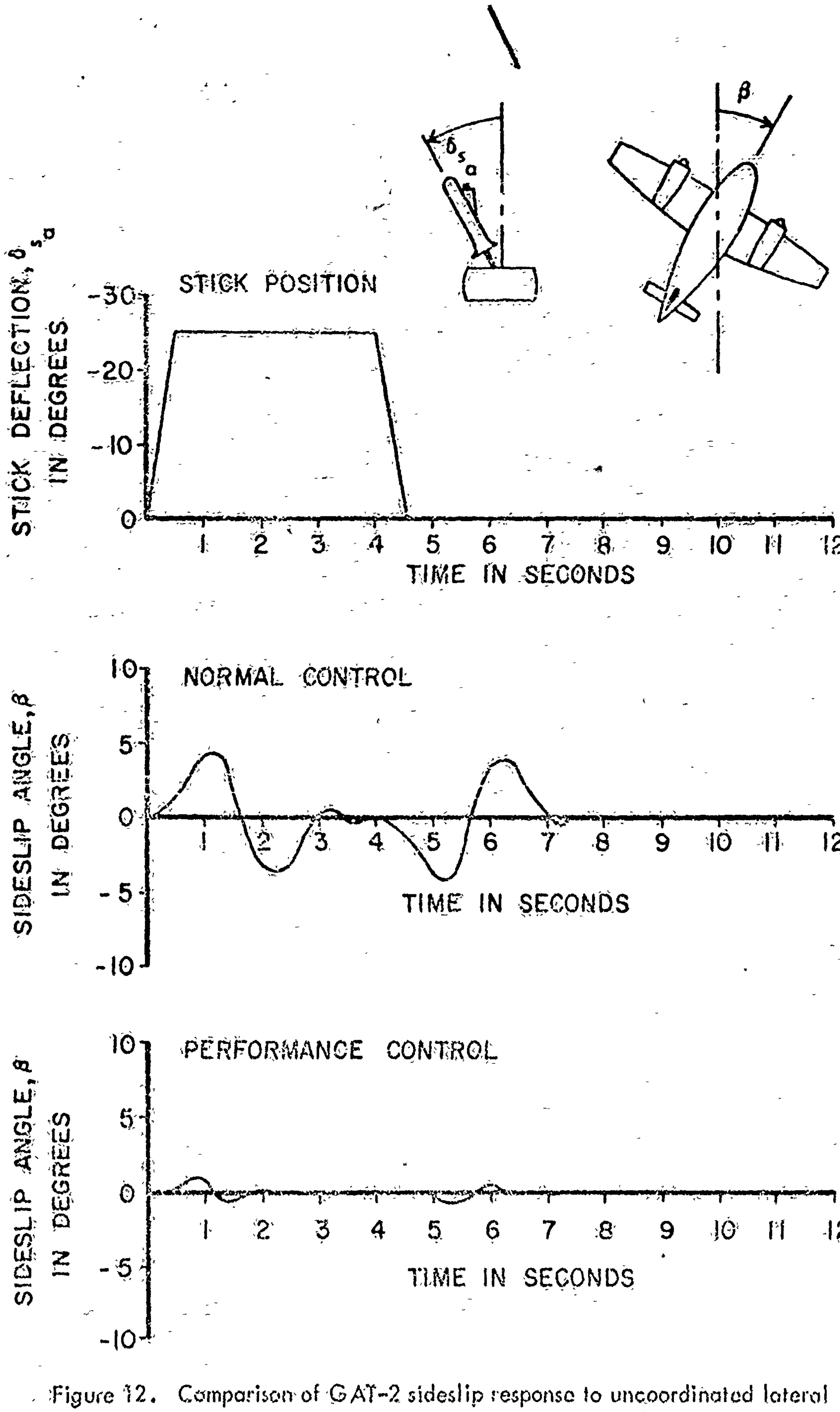


Figure 12. Comparison of GAT-2 sideslip response to uncoordinated lateral stick inputs with normal and performance controllers. Flight parameters are: indicated airspeed, 100 knots; altitude, 3000 feet; no turbulence.

the stick gain changes. This change in scale factor permit full authority over the required range of vertical speeds while allowing better precision of control for smaller vertical rates. Pilots generally considered the nonlinear control of climb and descent to be satisfactory in both modes, and preliminary experimentation involving maneuvering flight (page 14) has further shown the overall scaling to be very good. In Table 1, normal mode scale factors give elevator, total aileron, and rudder angles per respective stick angle. Performance mode scale factors give vertical rate, bank angle, and sideslip angle per respective stick angle. The sidearm stick axes are defined in Figure 5.

TABLE 1

Sidearm Stick Motion Limits and Scale Factors

Normal Control Mode		
Axis	Motion Limits	Scale
Pitch	$-16^\circ < \delta_{s_e} < +16^\circ$	2.0 deg/deg $(-10^\circ < \delta_{s_e} < +10^\circ)$ and 2.9 deg/deg $(-10^\circ > \delta_{s_e} > +10^\circ)$
Roll	$-25^\circ < \delta_{s_a} < +25^\circ$	1.6 deg/deg
Yaw	$-20^\circ < \delta_{s_r} < +20^\circ$	1.2 deg/deg
Performance Control Mode		
Axis	Motion Limits	Scale
Pitch	$-16^\circ < \delta_{s_e} < +16^\circ$	85 fpm/deg $(-10^\circ < \delta_{s_e} < +10^\circ)$ and 120 fpm/deg $(-10^\circ > \delta_{s_e} > +10^\circ)$
Roll	$-25^\circ < \delta_{s_a} < +25^\circ$	2.0 deg/deg
Yaw	$-20^\circ < \delta_{s_r} < +20^\circ$	0.5 deg/deg

Experimental Procedures

Each pilot subject was given a written set of instructions (Appendix A) several days prior to his first experimental session. Verbal instructions, including a description of the current experimental condition and answers to the subject's questions, were given before each flight.

The flight task consisted of a 35-minute flight in the Link GAT-2 under simulated instrument flight conditions. Pilots were given a clearance prior to takeoff directing them along a flight profile composed of a series of courses to eight successive waypoints. The pilots were also given a simulated area navigation chart that gave all necessary waypoint definition data and showed several waypoints in addition to the ones required for the flight. Each pilot was required to draw in the courses himself from the information given in the clearance. With few exceptions, pilots made two simulated flights in each of four experimental sessions. Time between sessions was one to three days.

Each flight began with a takeoff and climb to a 3000-foot altitude where radar vectors were given to steer the pilot to the interception of the first leg. The portion of the flight prior to interception of the first leg gave the pilot time to become sufficiently familiar with the experimental task before data taking was begun. Flight time on the area navigation course was approximately 28 minutes, depending on pilot technique. Entry to the first leg was accomplished by a left turn of approximately 45 degrees. At each waypoint, a turn of approximately 45 degrees was required. Successive turns were in opposite directions so that direction of turn was counterbalanced within each flight. The magnitude of each course change differed slightly from 45 degrees so that no course would exactly coincide with a previous course. Pilots were instructed to change the TRACK setting on the SPI as they approached and crossed over each waypoint, to initiate turns to a new course not more than one nautical mile before reaching a waypoint, and to make all turns at the standard rate of 3 degrees per second or less. A clearance to land was issued after the last waypoint was passed.

Simulated atmospheric conditions included a daytime, in-cloud environment, a steady wind from the west at 20 knots, and continuous light-moderate turbulence. Cruise airspeed was 180 knots.

Residual attention measurement through side-task loading was used during the first of two replications of the experiment. Prior to each flight, the pilot was verbally instructed to give primary attention to the flight task and to respond to numerical stimuli only if he were sure that the extra workload involved would not adversely affect flight control.

Experimental Design

Independent variables in the design included control mode (normal versus performance), waypoint storage capacity (1, 2, 4, or 8), and side-task loading (present or absent). Dependent variables were tracking errors (altitude and crosstrack errors), procedural errors (blunders), and residual attention (bits of information processed per unit time). The counterbalanced orders of serial presentation of experimental conditions, shown in Table 2, were applied to eight pilot subjects in each of the two independent replications of the experiment, with and without side-task loading. Thus, each replication included control modes, number of waypoints stored, and pilots (eight different pilots in each replication) as factors.

In Table 2, pilots are shown arranged in groups of four pilots each. Group one (pilots 1, 2, 3, 4) and group three (pilots 9, 10, 11, 12) began with four flights using normal control and finished with four flights using performance control. Group two (pilots 5, 6, 7, 8) and group four (pilots 13, 14, 15, 16) started with the performance control mode and finished with normal control.

Subjects

Precision of aircraft control and procedural errors may be expected to vary with the total experience and currency of the individual pilot. For this reason, the pilot subjects selected were required to have valid instrument ratings

TABLE 2

Serial Orders of Presentation of Eight Experimental Conditions to Eight Pilots in Each of Two Independent Groups Tested with and Without Side-Task Loading (Numbers in Body of Table Represent Waypoint Storage Capacity)

Pilot	Trial 1	2	3	4	1	2	3	4
	Normal Control				Performance Control			
1, 9	1	8	2	4	8	4	1	2
2, 10	2	1	4	8	4	2	8	1
3, 11	4	2	8	1	2	1	4	8
4, 12	8	4	1	2	1	8	2	4
	Performance Control				Normal Control			
5, 13	1	8	2	4	8	4	1	2
6, 14	2	1	4	8	4	2	8	1
7, 15	4	2	8	1	2	1	4	8
8, 16	8	4	1	2	1	8	2	4

and to have had previous RNAV experience. Table 3 summarizes the age and flight experience of the subjects. Pilots were recruited from the staff of the University of Illinois Institute of Aviation and were randomly assigned to each subject position.

TABLE 3

Age and Flight Experience of Pilot Subjects Who Flew Simulated Area Navigation Flight Profiles with Side-Task Loading (Pilots 1-8) and Without Side-Task Loading (Pilots 9-16)

Flight Experience in Hours				
Pilot	Total	Instrument	RNAV	Age in Years
1	3500	100	5	30
2	2250	150	8	27
3	2400	150	4	29
4	350	75	10	26
5	1500	150	2	29
6	410	60	3	22
7	1600	140	8	25
8	1600	150	20	31
Mean	1701	122	7.5	27
9	3400	150	5	26
10	1400	100	2	24
11	500	50	5	25
12	7200	350	8	40
13	8000	200	2	47
14	265	40	3	28
15	880	60	5	24
16	3300	250	6	33
Mean	3118	150	4.5	31

RESULTS

Flight Control

Ground coordinates and altitude of the simulated flight path were recorded at 5-second intervals throughout each flight. Errors in track and altitude were calculated for each of the recorded points. These errors were then interpolated to uniform 0.25-nmi intervals along the true course so that pointwise comparisons of course-keeping and altitude-keeping could be made across all flights at specific course positions.

Crosstrack errors were measured from true course lines between successive waypoints, rather than from the corresponding track or radial for the waypoint in use. Consequently, measured errors include any small errors in setting the TRACK selector on the SPI. There were two reasons for choosing this measure: first, no meaningful errors relative to track were available while switching waypoints in the condition allowing single waypoint storage; and second, small crosscourse errors due to errors in the track setting were a valid part of total pilotage error.

Flight control accuracy was most strongly affected by control mode, side-task loading, pilot learning, and proximity to waypoints (that is, whether turning at a waypoint or flying straight along a leg between waypoints). Each of these factors produced a large and statistically reliable ($p < .01$) effect on the precision of manual flight control.

Table 4 gives the means and standard deviations of the crosstrack and altitude errors for each of these effects. Mean error, $\bar{X}$, representing central tendency, is found as follows:

$$\bar{X} = \frac{\Sigma x_i}{N}$$

where:

x_i is the individual error measurement at each .25-nmi point for each flight, or portion thereof, under the designated condition,

TABLE 4

Means and Standard Deviations of Crosstrack and Altitude Errors with Normal and Performance Controllers, Showing Overall Results and Effects of Side-Task Loading, Learning, and Proximity to Waypoints

Condition	Control Mode	Crosstrack Errors in Nautical Miles		Altitude Errors in Feet	
		Mean	Standard Deviation	Mean	Standard Deviation
Overall	Normal Performance	.16 .08	.42 .24	33 2	124 22
With Side Task	Normal Performance	.22 .11	.49 .31	36 4	144 27
Without Side Task	Normal Performance	.11 .04	.32 .12	30 0	101 17
First Flight	Normal Performance	.24 .10	.51 .34	75 2	182 25
Last Flight	Normal Performance	.12 .07	.34 .17	13 1	82 21
Between Waypoints (Straight)	Normal Performance	.17 .07	.40 .23	32 1	125 23
Over Waypoints (Turning)	Normal Performance	.16 .08	.50 .29	42 5	126 23

N is the number of values of x_i for which the mean is found.

Standard deviation, σ, representing variability about the mean, is found as follows:

$$\sigma = \sqrt{\frac{\Sigma x_i^2}{N-1} - \bar{X}^2}\ .$$

Means and standard deviations of crosstrack and altitude errors for each trial are presented in Appendix B. The overall results, shown in Table 4, demonstrate the general superiority of the performance control mode in accuracy of flight control. The overall mean and standard deviation of crosscourse errors with the performance controller were half as great as with normal control. Pilots uniformly found altitude-keeping to be more difficult than course-keeping. Nevertheless altitude errors with performance control, regardless of condition, averaged close to zero, and standard deviations of altitude errors were of the same order of magnitude as the smallest division on the altimeter (20 feet). With the normal controller, altitude errors were much greater.

Secondary Task Effects. Side-task loading had a large effect on pilotage errors with both controllers. Note in Table 4 that the percentage decrement in performance due to elevated workload is greater with the performance controller than with the normal controller, also that crosstrack errors generally increase proportionately more than altitude errors when the side task is added. Both of these effects agree with other research which shows that the easier of two tasks suffers the greater performance decrement under conditions of elevated workload (Kamlet, 1965; Klemmer, 1956a; Levison and Elkind, 1966; Lindsay, Cuddy, and Tulving, 1965; Mowbray, 1952, 1953; Suboski, 1966; Tulving and Lindsay, 1967).

Learning Effects. Every pilot made four sequential flights with each control mode. The data in Table 4 for the "first flight" condition represent all flights in which the pilot used the designated controller for the first time; and the "last flight" condition represents all flights in which the designated controller was used for the

last (fourth) time. Learning effects reduced crosstrack and altitude errors with both controllers. The magnitudes of the reductions due to learning were greater for the normal controller; nevertheless, the performance control mode maintained a large margin of superiority.

Table 5 separates the learning effects presented in Table 4 into conditions with or without side-task loading. Improvements with learning were greater with the side task present, due to the higher "first flight" errors caused by the elevated workload. Again, with or without the side task, improvements in flight accuracy were greater with the normal controller, but "last flight" accuracy was still better with performance control.

Figures 13 through 19 present learning effects on root mean square (RMS) crosstrack and altitude errors. RMS error is found as follows:

$$\mathrm{RMS} = \sqrt{\frac{\Sigma x_i^2}{N-1}}$$

RMS error represents variability about the centerline of a course rather than about the mean, or central tendency, of the flight paths. RMS errors presented are calculated from all sample points for each condition. Each point plotted in Figures 13 through 19 represents RMS error calculated across four flights by the four subjects who used the controllers in the same order. The only difference in experimental sequencing between pilots in a group (defined on page 34) was the order of presentation of waypoint storage capacity.

Figure 13 shows the effects of learning on RMS crosstrack errors for complete flights. With side-task loading, learning became asymptotic at the sixth or seventh flight. Without the side task, learning leveled off at the fourth flight. Note that when pilots in groups 2 and 4 switched from the performance mode to the normal mode on the fifth trial, the RMS crosstrack errors increased. On the other hand, groups 1 and 2 continued to improve when the change was made from normal to performance control. Figures 14 and 15 present the learning effects on RMS

TABLE 5

Means and Standard Deviations of Crosstrack and Altitude Errors with Normal and Performance Controllers, Showing Effects of Learning and Proximity to Waypoints with and without Side-Task Loading

	Condition	Control Mode	Crosstrack Errors in Nautical Miles		Altitude Errors in Feet	
			Mean	Standard Deviation	Mean	Standard Deviation
With Side Task	First Flight	Normal Performance	.32 .15	.59 .45	104 5	213 31
With Side Task	Last Flight	Normal Performance	.14 .10	.39 .22	3 2	78 23
With Side Task	Between Waypoints (Straight)	Normal Performance	.23 .11	.46 .29	35 3	146 27
With Side Task	Over Waypoints (Turning)	Normal Performance	.22 .12	.58 .37	42 7	149 27
Without Side Task	First Flight	Normal Performance	.15 .04	.39 .13	46 0	140 17
Without Side Task	Last Flight	Normal Performance	.11 .04	.28 .11	24 0	85 17
Without Side Task	Between Waypoints (Straight)	Normal Performance	.11 .03	.30 .11	28 0	99 17
Without Side Task	Over Waypoints (Turning)	Normal Performance	.11 .04	.39 .17	42 2	98 17

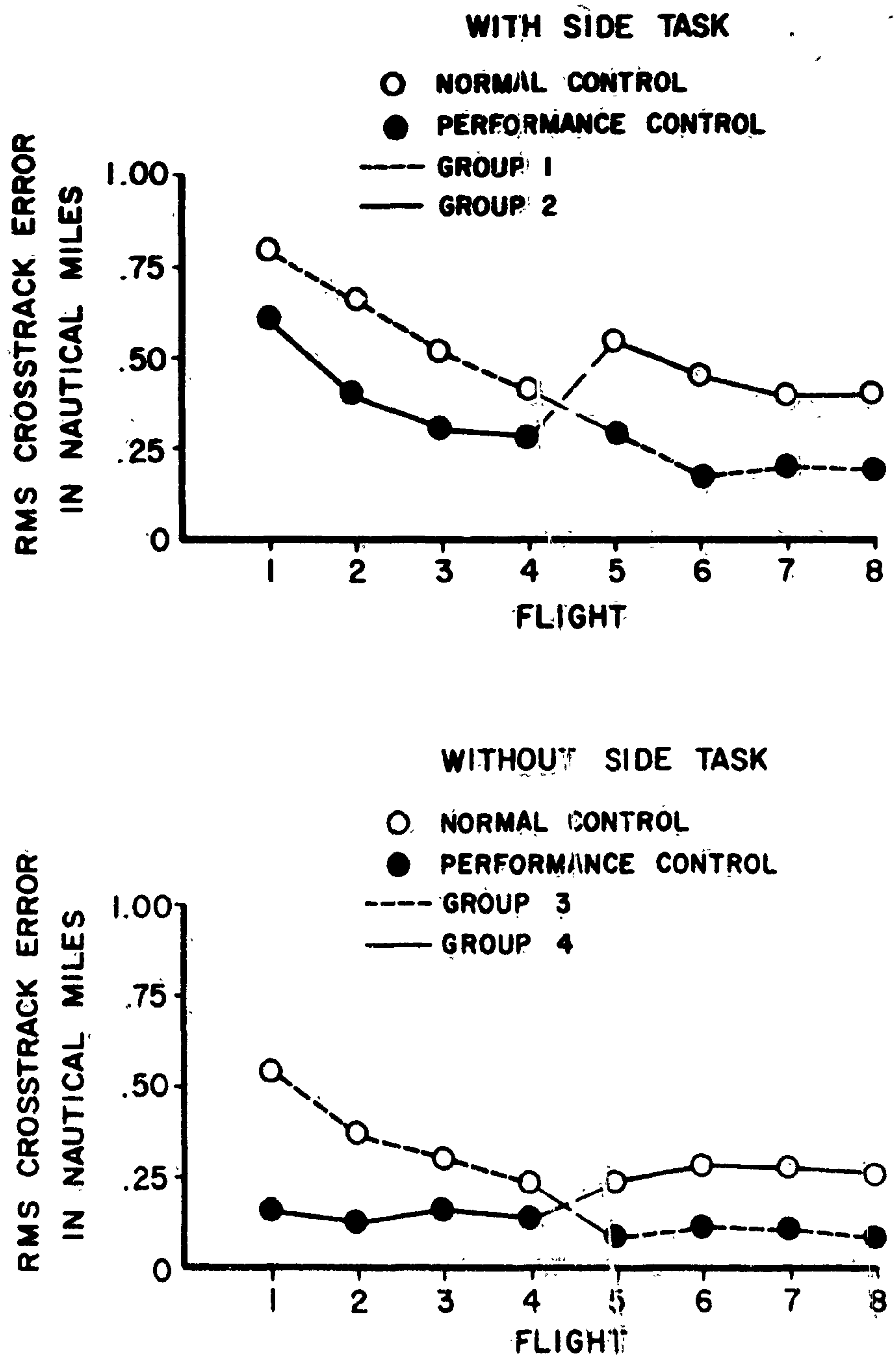


Figure 13. Comparison of effects of learning on RMS crosstrack errors for complete flights with normal and performance controllers, with and without side-task loading. Longer dashed lines connect performances of groups of four pilots each.

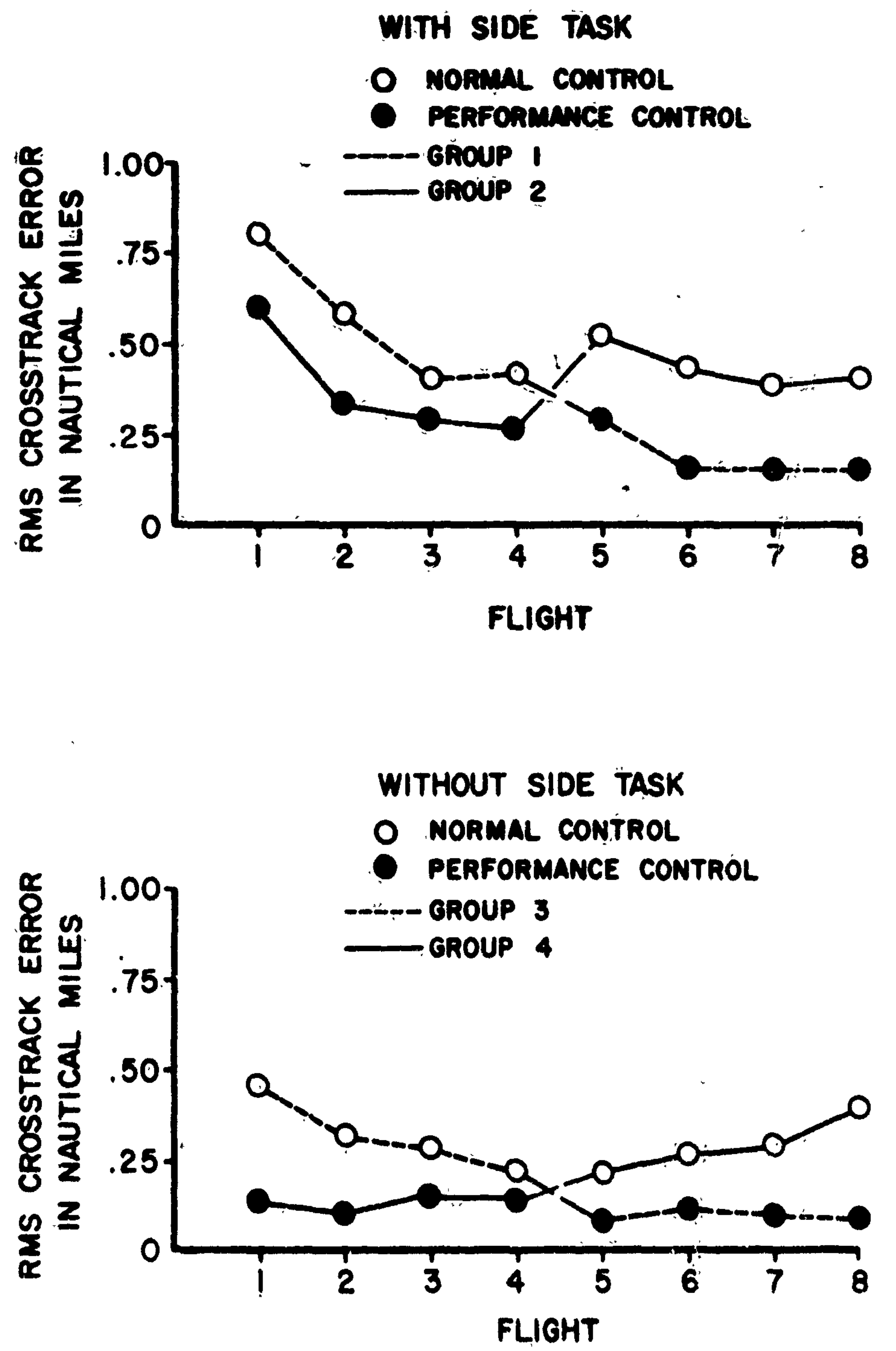


Figure 14. Comparison of effects of learning on RMS crosstrack errors between waypoints with normal and performance controllers, with and without side-task loading. Longer dashed lines connect performances of groups of four pilots each.

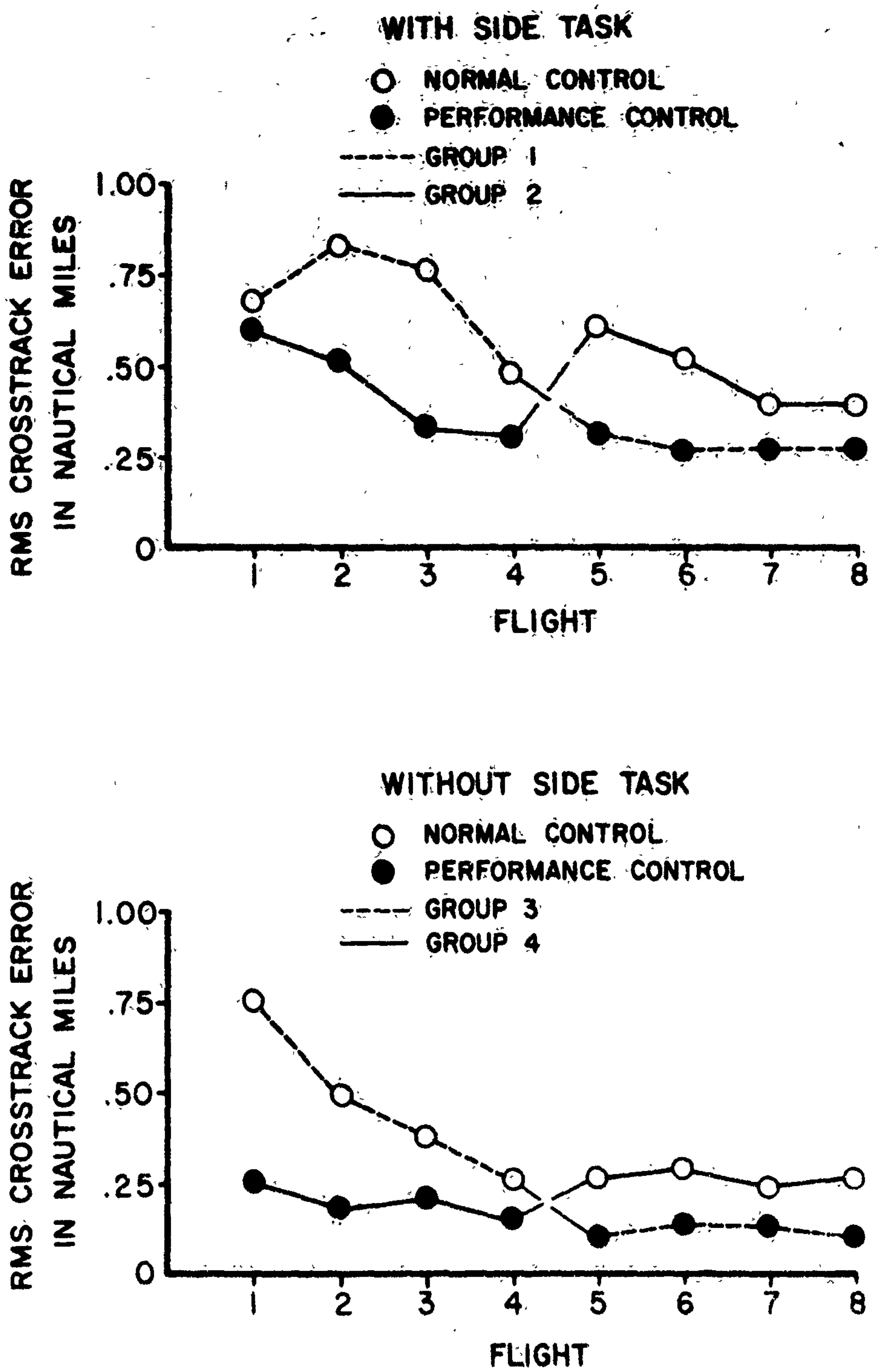


Figure 15. Comparison of effects of learning on RMS crosstrack errors over waypoints with normal and performance controllers, with and without side-task loading. Longer dashed lines connect performances of groups of four pilots each.

crosstrack errors in straight (between waypoints) flight and turning (over waypoints) flight, respectively. When aircraft alongtrack position was within 1.5 nmi of a waypoint, it was sc d to be "over the waypoint" in question. At greater along-track distances than 1.5 nmi from a waypoint, the flight was said to be "between waypoints." Learning effects for straight and turning flight segments followed the same general trends as in Figure 13 for complete flights. However, group 1 pilots had higher errors in turns during their second and third flights than during their first flights, possibly due to stress and fatigue resulting from these difficult conditions. Group 4 pilots lost some enthusiasm for the experiment after switching to normal control, and this appears to have affected crosstrack errors between waypoints.

An accepted method of turning at intersecting airways is to lead the turn so as to cut inside of the actual intersection. An alternative method, also used, is to fly over the intersection in order to get a positive indication of interception of the new radial and then to turn back to that radial. The first method usually involves lower crosstrack errors than the second and is preferred for navigational flight. Figure 16 presents learning effects on mean crosstrack errors during turns over way-points. Group 1 pilots, whose problems with turns have already been noted, overshot the waypoints initially and then overcompensated by cutting the turns too early in their second and third flights. Figure 16 shows three cases of general overshoot for the normal controller as compared to one case with the performance controller. On the whole, pilots learned to lead the turns consistently after four flights.

Figure 17 shows the effects of learning on RMS altitude errors for complete flights. Learning was negligible for the performance control mode, probably because the small altitude errors realized in this mode were difficult to detect on the altimeter. With the side task, normal control altitude errors for group 1 leveled off at the third flight. Group 2 pilots had considerable difficulty with altitude-holding upon switching to normal control and continued learning through the eighth flight. Without the side task, group 3 errors with normal control

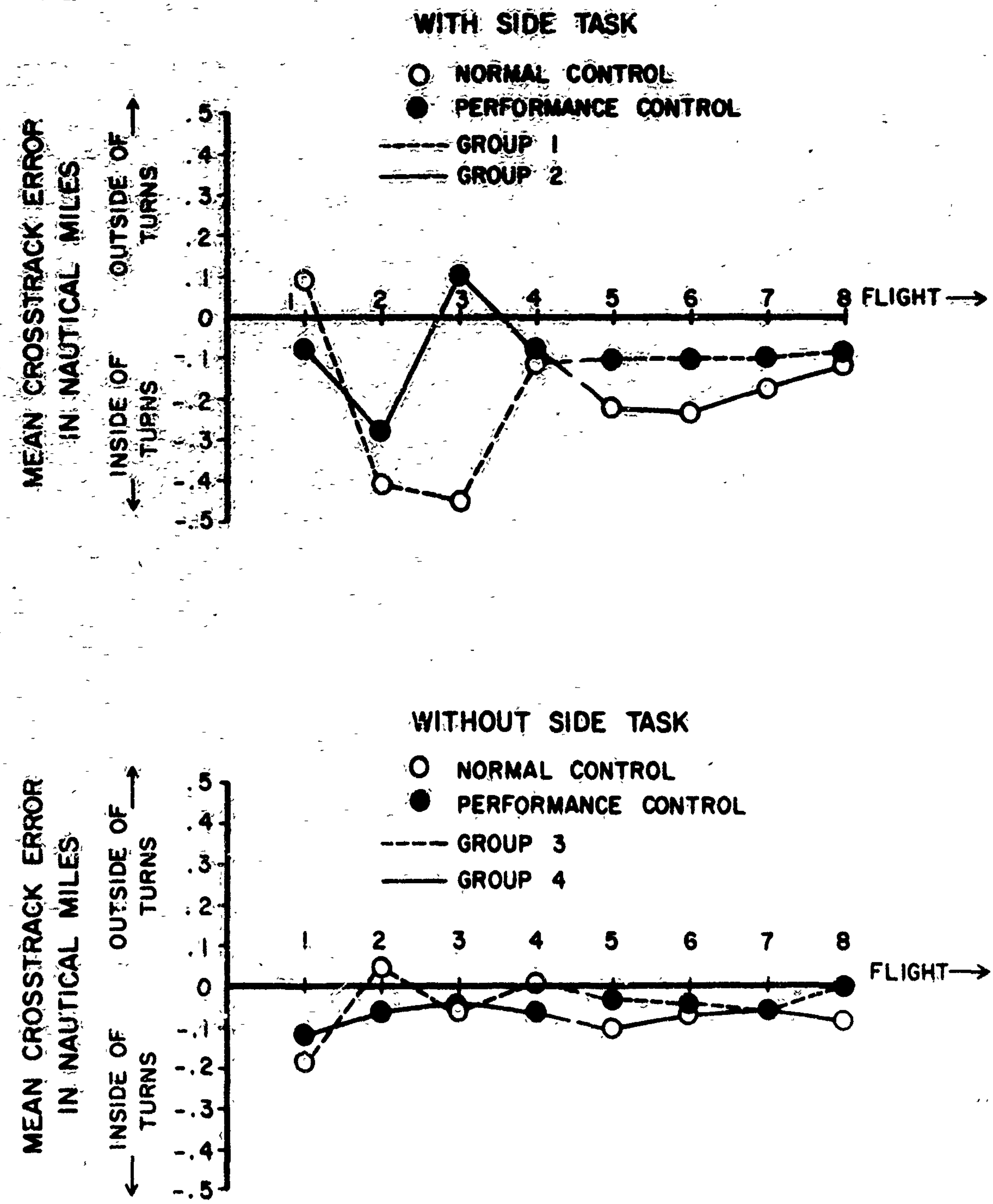
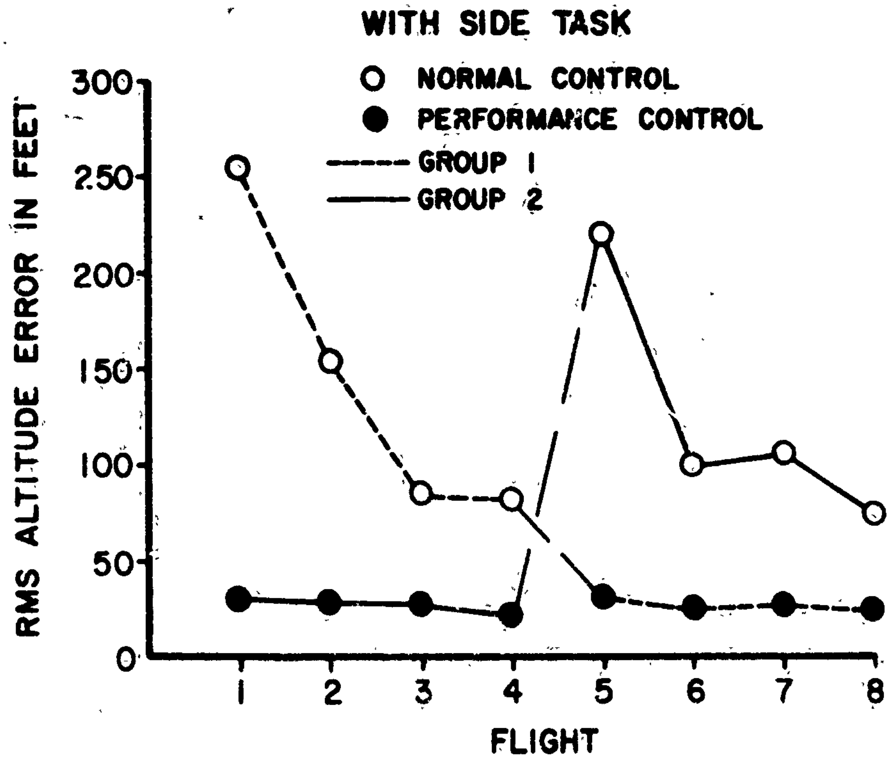


Figure 16. Comparison of effects of learning on mean crosstrack errors over waypoints with normal and performance controllers, with and without side-task loading. Longer dashed lines connect performances of groups of four pilots each.



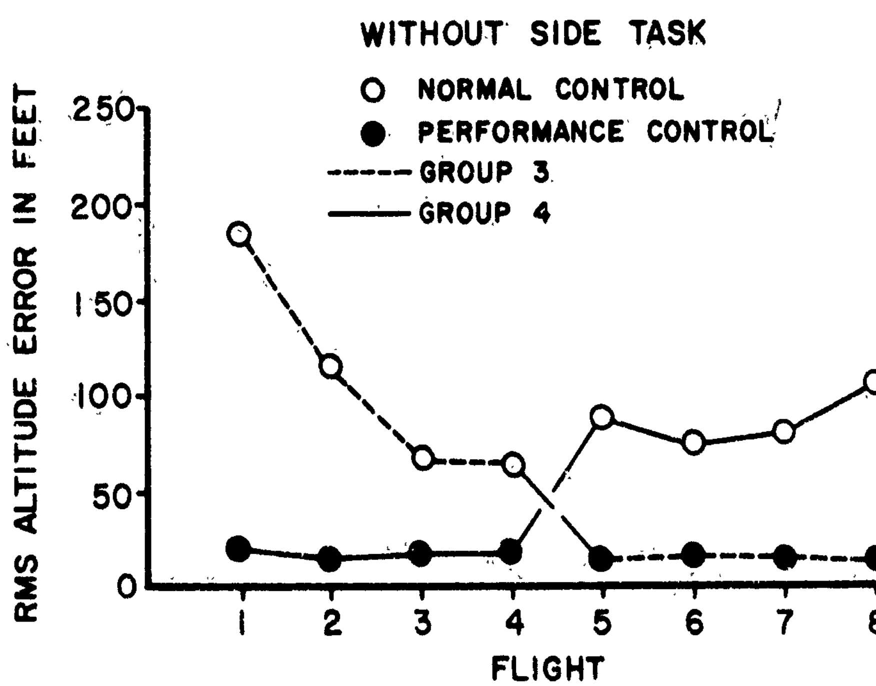


Figure 17. Comparison of effects of learning on RMS altitude errors for complete flights with normal and performance controllers, with and without side-task loading. Longer dashed lines connect performances of groups of four pilots each.

leveled off at the third flight. Group 4 pilots never achieved the same accuracy with normal control as group 3. Best results for group 4 occurred in the sixth flight. The previously mentioned, gradually decreasing motivation of this group led to increasing RMS altitude errors for the last two trials. Figures 18 and 19 present learning effects on RMS altitude errors in straight and turning flight. Results are generally similar to Figure 17.

Effects of Proximity to Waypoints. Crosstrack errors would be expected to increase in the vicinity of waypoints due to overshooting or cutting inside of turns. Using normal control, a small increase in altitude errors would also be expected over waypoints due to the increased navigational workload, as well as to the extra coordination required to hold altitude. Standard deviations of crosscourse and altitude errors presented in Tables 4 and 5 show some indication of these effects. More complete indications of the effects of waypoint proximity on flight control errors are given in Figures 20 and 21. The graphs combine data for 32 flights into a single leg and turn at a waypoint, and show the $\pm 1\sigma$ envelopes of crosstrack and altitude errors for the flights plotted about their means at 0.25-nmi intervals along a course line beginning 10.75 nmi prior to a waypoint and extending 1.5 nmi beyond the waypoint. The waypoint shown in each case in Figure 20 is a composite waypoint in that it represents waypoints where either left or right turns were made. Mean crosstrack errors appear to remain fairly constant throughout each condition. Standard deviations, however, definitely increase in the turns, and the variability introduced near the waypoints takes many miles to settle out. The approximate wind direction is shown in Figure 20 and accounts for the fact that mean crosstrack errors were to the right of course.

In Figure 21, means and standard deviations of altitude errors are plotted above and below the flight path, and the segment to the right of the waypoint is straightened out to prevent foreshortening of the courseline and data. With the normal controller, the mean and variability of altitude errors increase noticeably in the turns. Where the side task is present, variability in the middle of straight

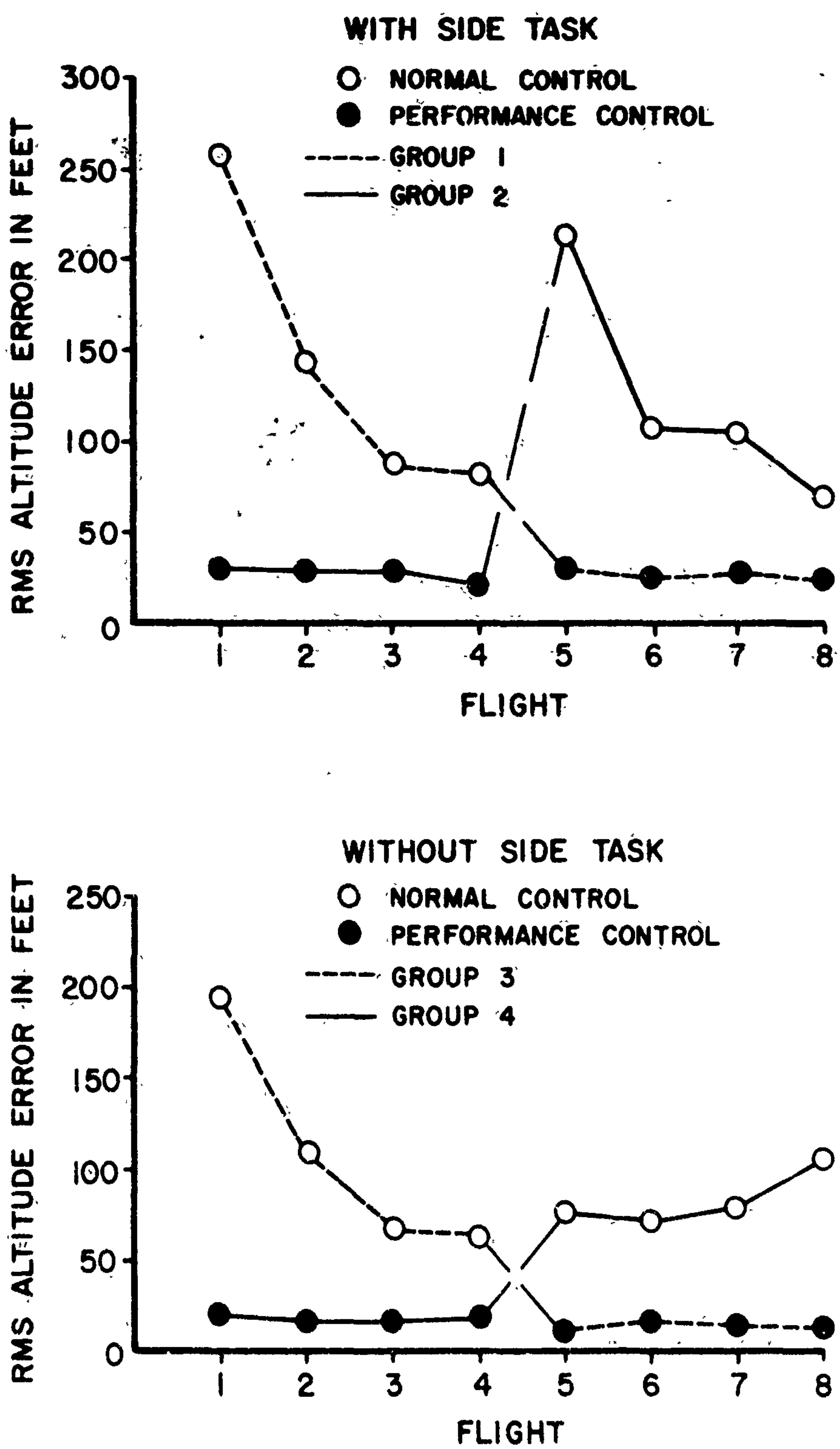
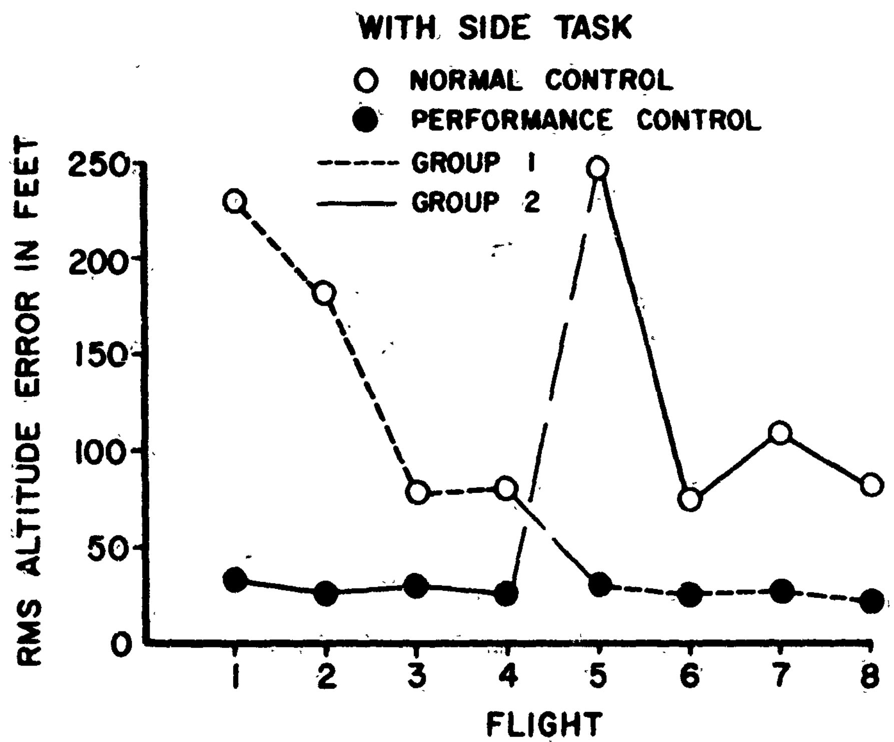


Figure 18. Comparison of effects of learning on RMS altitude errors between waypoints with normal and performance controllers, with and without side-task loading. Longer dashed lines connect performances of groups of four pilots each.



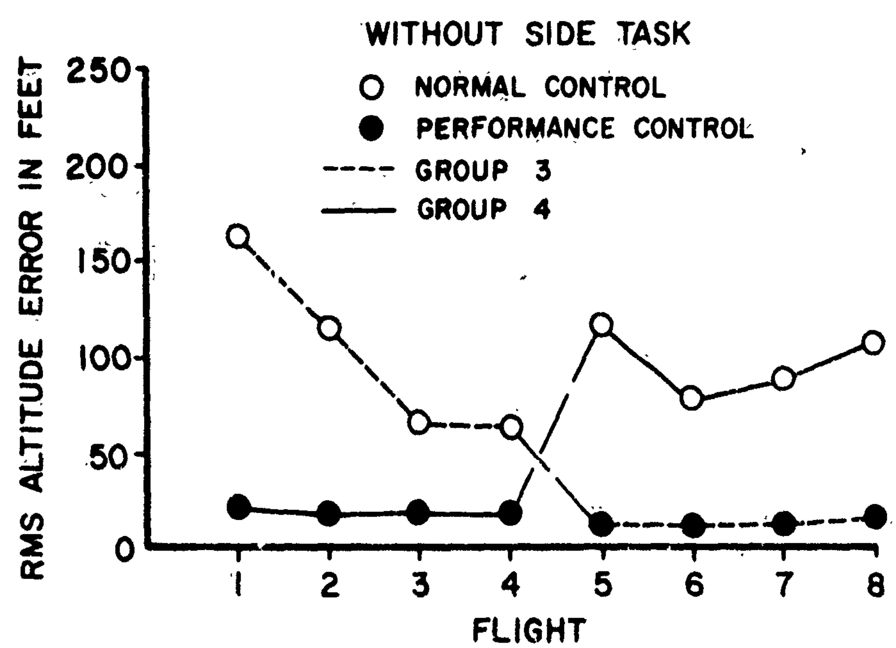


Figure 19. Comparison of effects of learning on RMS altitude errors over waypoints with normal and performance controllers, with and without side-task loading. Longer dashed lines connect performances of groups of four pilots each.

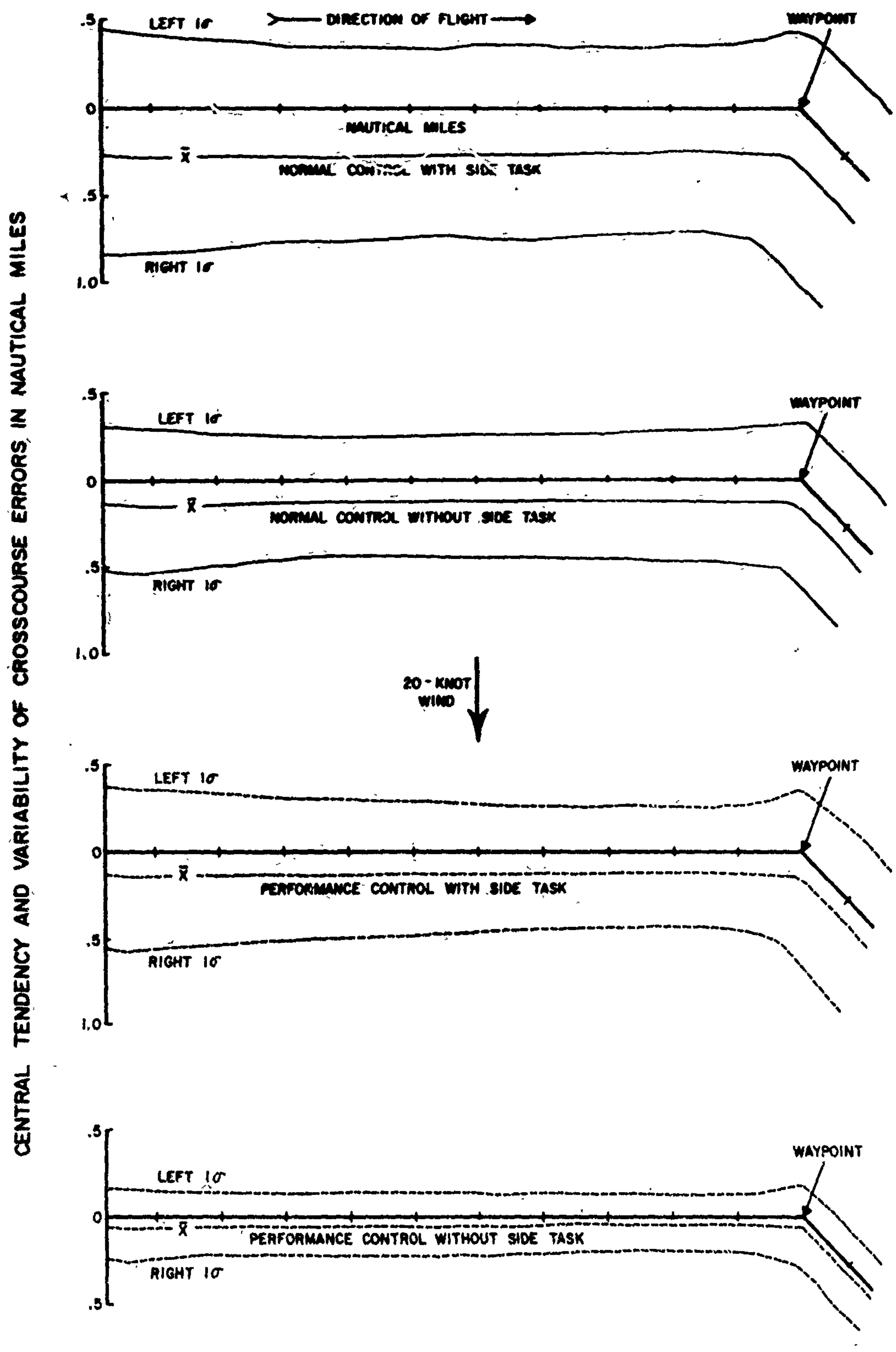


Figure 20. Central tendency and variability of crosscourse error as a function of distance from a waypoint averaged for eight route segments of 12 nmi each.

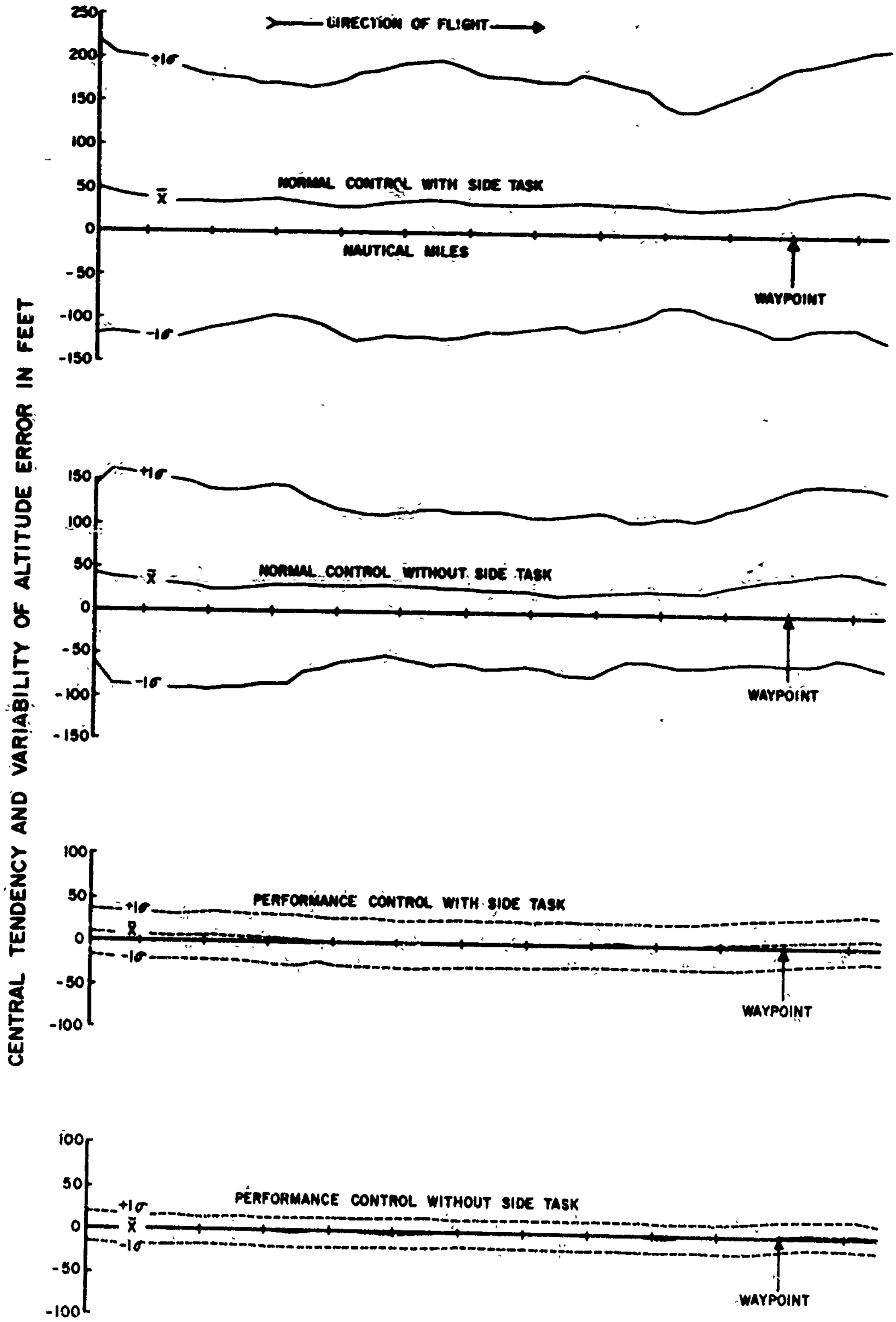


Figure 21. Central tendency and variability of altitude error as a function of distance from a waypoint averaged for eight route segments of 12 nmi each.

legs (where new waypoint data are entered) is also high. With the performance controller, differences along the course are very small. With side-task loading, the mean error becomes noticeable in turns and does not disappear for 5 nmi after the waypoint. Overall, pilots tended to fly above the true flight path, especially with the normal controller.

Figures 22 through 25 separate the data in Figures 20 and 21 into "northbound" legs with right turns and "northeast" segments with left turns. The mean and variability of crosscourse errors for each general direction of flight, shown in Figures 22 and 23, follow the same general form as in Figure 20. One exception is the effect of wind on turn errors. In right turns the wind keeps the flight path inside the turn, whereas in left turns, the mean crosstrack errors cross the courseline twice. Also, variability is generally higher in left turns than in right turns.

Figures 24 and 25 give the mean and variability of altitude errors for each general direction of flight. With the normal control and side-task loading on northeast legs, altitude errors are greater over straight segments than in left turns, but less than in right turns. Without the side task, errors with the normal controller were higher in turns than in straight segments. Altitude errors with the performance controller were uniformly low.

Procedural Blunders

In each flight there were 56 procedural operations associated with area navigation that provided opportunities to blunder at least once. Thus, each of the two experimental replications presented a total of 3,584 blunder opportunities. For each pilot, the number of blunder opportunities in eight flights was 448. Appendix C presents the total number of procedural errors for each trial.

Total blunders by each of the pilots correlated highly with their individual overall performances on the flight task. In the first replication, with side-task loading, pilot blunders correlated +.89 with RMS crosstrack errors and +.71 with RMS altitude errors. Without side-task loading, blunders correlated +.48 with RMS crosstrack errors and +.83 with RMS altitude errors.

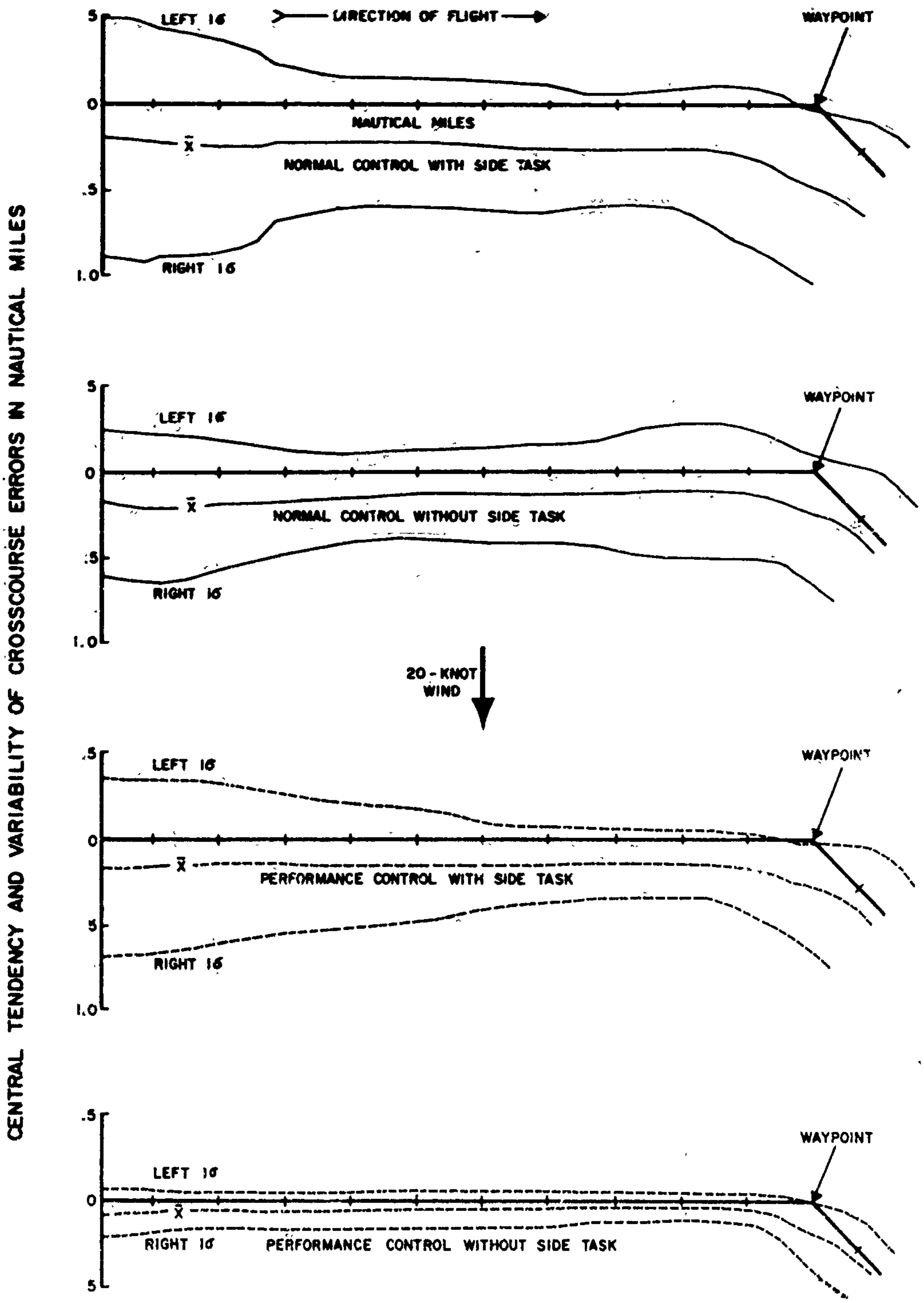


Figure 22. Central tendency and variability of crosscourse error as a function of distance from a waypoint averaged over four "northbound" legs with right turns.

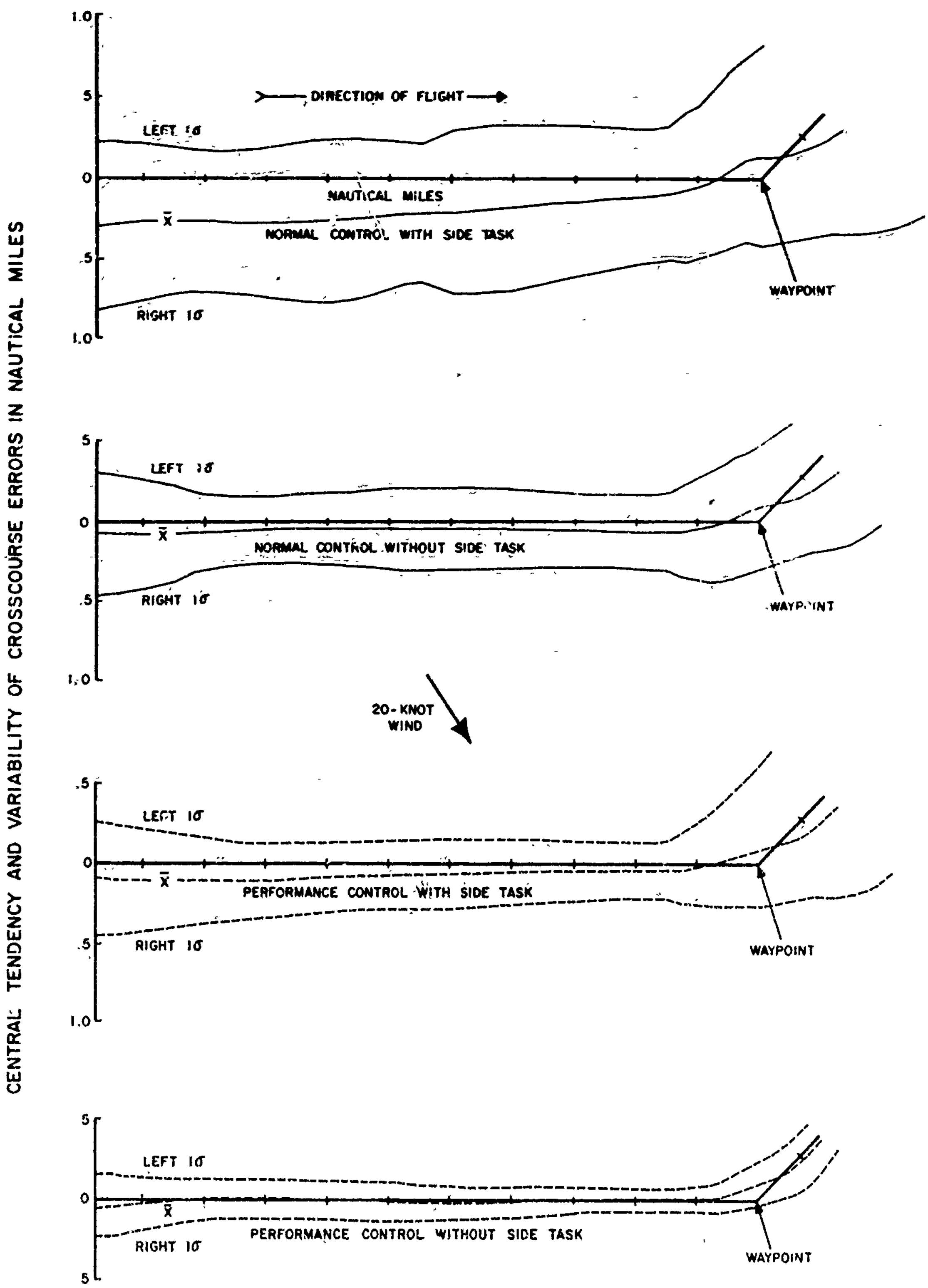


Figure 23. Central tendency and variability of crosscourse error as a function of distance from a waypoint averaged over four "northeast" legs with left turns.

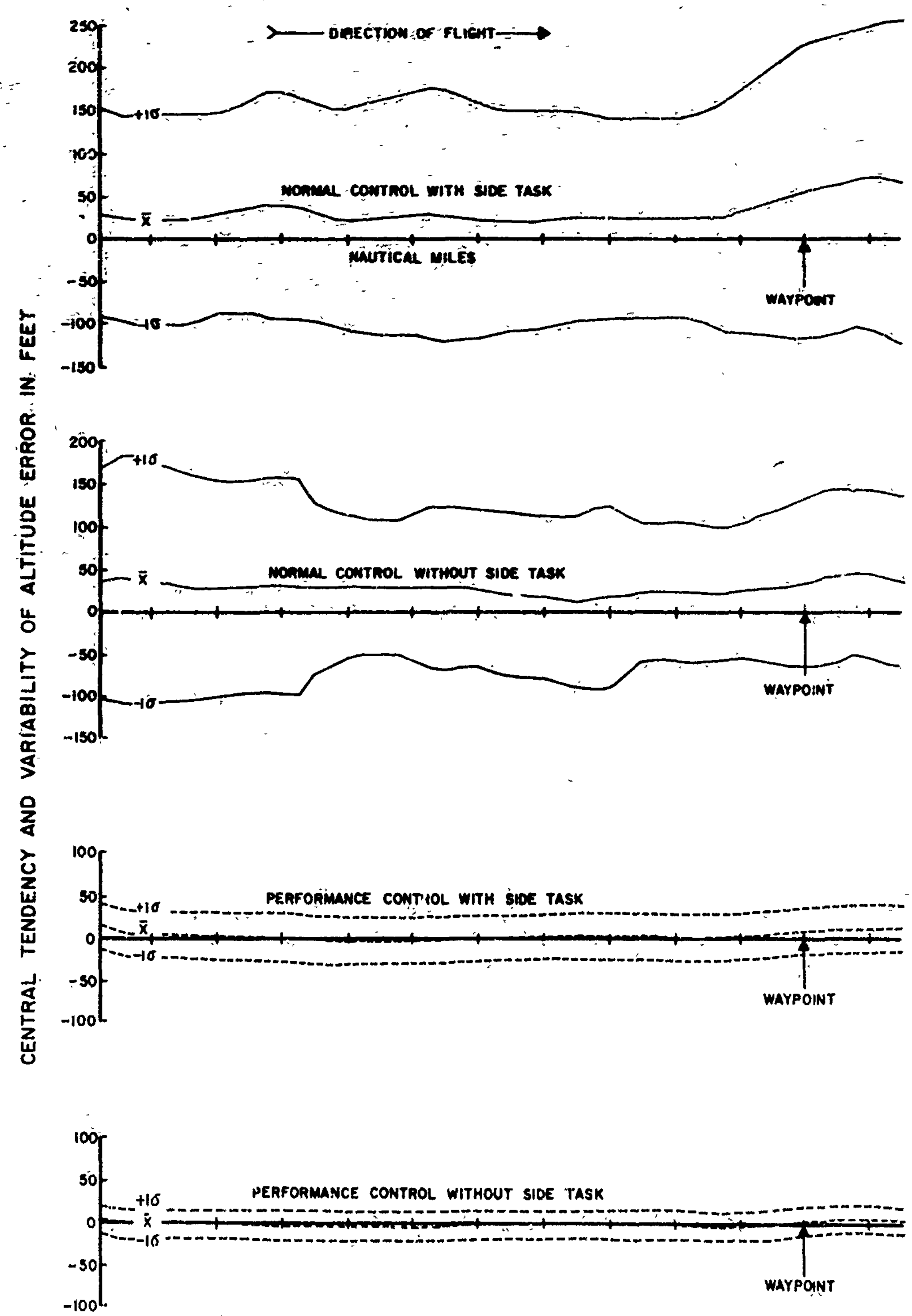


Figure 24. Central tendency and variability of altitude error as a function of distance from a waypoint averaged over four "northbound" legs with right turns.

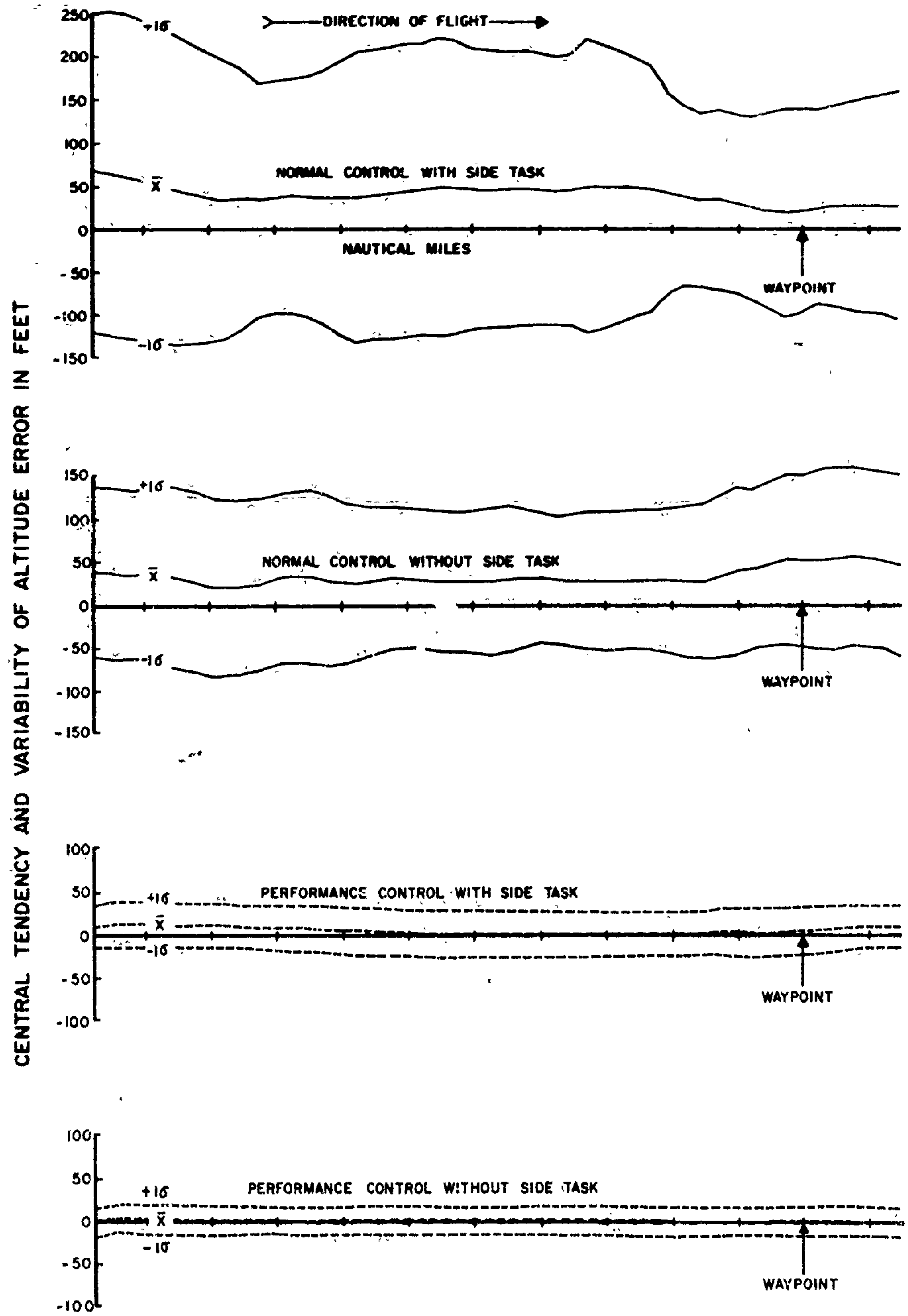


Figure 25. Central tendency and variability of altitude error as a function of distance from a waypoint averaged over four "northeast" legs with left turns.

Controller and Side-Task Effects. In the first of the two replications, during which side-task loading was used, 92 blunders were committed, 83 with normal flight control and 9 with performance control. In the second of the two replications, without side-task loading, 44 blunders were committed, 40 with normal flight control and 4 with performance control. Mean values for the various experimental conditions are summarized in Figure 26.

Thus, side-task loading forced an increase in blunders of more than two to one but did not change the fact that, with normal control, blunders were approximately ten times more prevalent than with performance control. Although frequency data such as these cannot be tested for statistical significance in any reasonably sanitary manner, there is little doubt concerning the reliability of frequency shifts of such a magnitude.

Table 6 gives a breakdown of total procedural blunders for the two replications. Frequency, radial, and distance blunders are associated with input errors on the control-display unit, while track and missed waypoint blunders are generally associated with misuse of the SPI. Missed waypoint blunders usually occurred when a pilot took too long to enter data for an upcoming waypoint and passed over the waypoint in use without noticing passage on the SPI. On four occasions, however, a waypoint was missed when the pilot inadvertently destroyed the data for the waypoint in use while attempting to enter upcoming data. The comparison of total blunders for each category shows that frequency, radial, distance, and track input blunders approximately doubled with the addition of side-task loading, while missed waypoint blunders increased nearly fourfold.

Waypoint Storage Capacity Effects. Figure 26 also illustrates the blunder-reducing effect of increasing waypoint storage capacity in area navigation computers. The effect is most evident, and no doubt most important, with side-task loading while coping with the workload demands of normal flight control. The eight pilots who flew without side-task loading each performed a total of 448 area navigation procedural operations without blunder while flying with performance control and a computer storage capacity for either four or eight navigation waypoints.

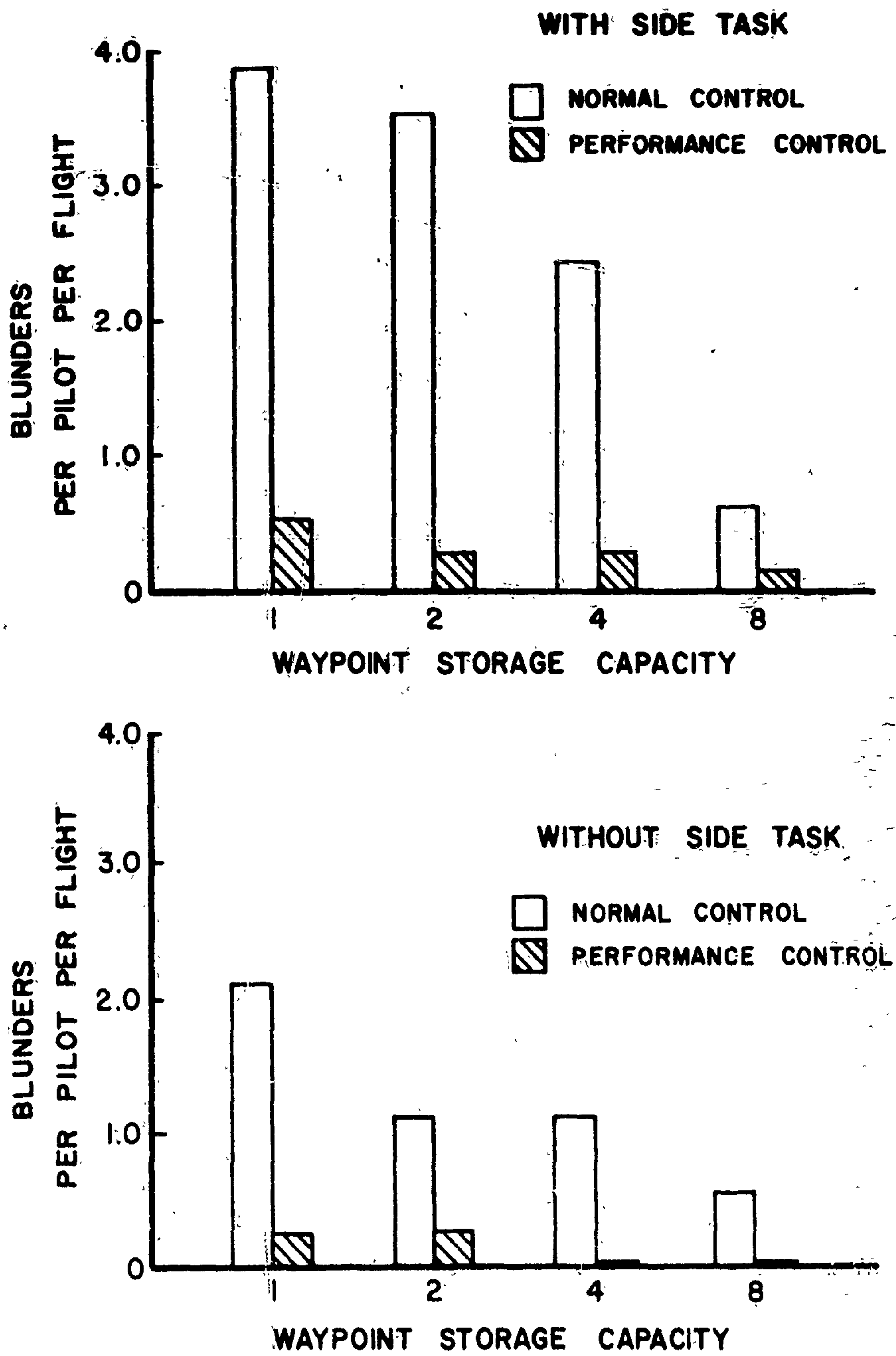


Figure 26. Area navigation procedural blunders as a function of computer waypoint storage capacity for normal control and flight performance control, with and without side-task loading.

TABLE 6

Classification of Total Procedural Errors with and Without Side-Task Loading

Condition	Type of Error					TOTAL
	VOR FREQ	WPT RAD	WPT DIST	WPT TRACK	MISSED WPT	
With Side Task	19	11	13	22	22	92
Without Side Task	10	6	7	13	6	44

Learning Effects. Whereas pilots were still learning to cope with the specific area navigation procedures called for after four flights with normal control, they evidently reached asymptotic performance almost immediately when flying with the performance controller. These effects are shown as functions of practice in Figure 27.

With the performance controller, side-task loading induced a few blunders on first and second trials only. Thereafter no blunders were made. Using the performance controller without side-task loading, an occasional blunder was made during later trials, possibly attributable to boredom.

Residual Attention

With the side task operative, 26,301 responses were recorded. This amounted to an average of 3,288 responses per pilot at average rates of approximately 411 per 27.7-minute trial, 14.8 per minute, or 0.247 per second. At three bits per response, this represented an information processing rate of 0.742 bits per second. Of the 26,301 responses, 14,817 were made while using the performance controller, at the average rate of 0.837 bits per second, and 11,484 were made while using normal control, at the average rate of 0.649 bits per second. These and all other comparisons presented are statistically reliable at well beyond the $p < .01$ level of confidence. Appendix D presents the total number of side-task responses for each trial.

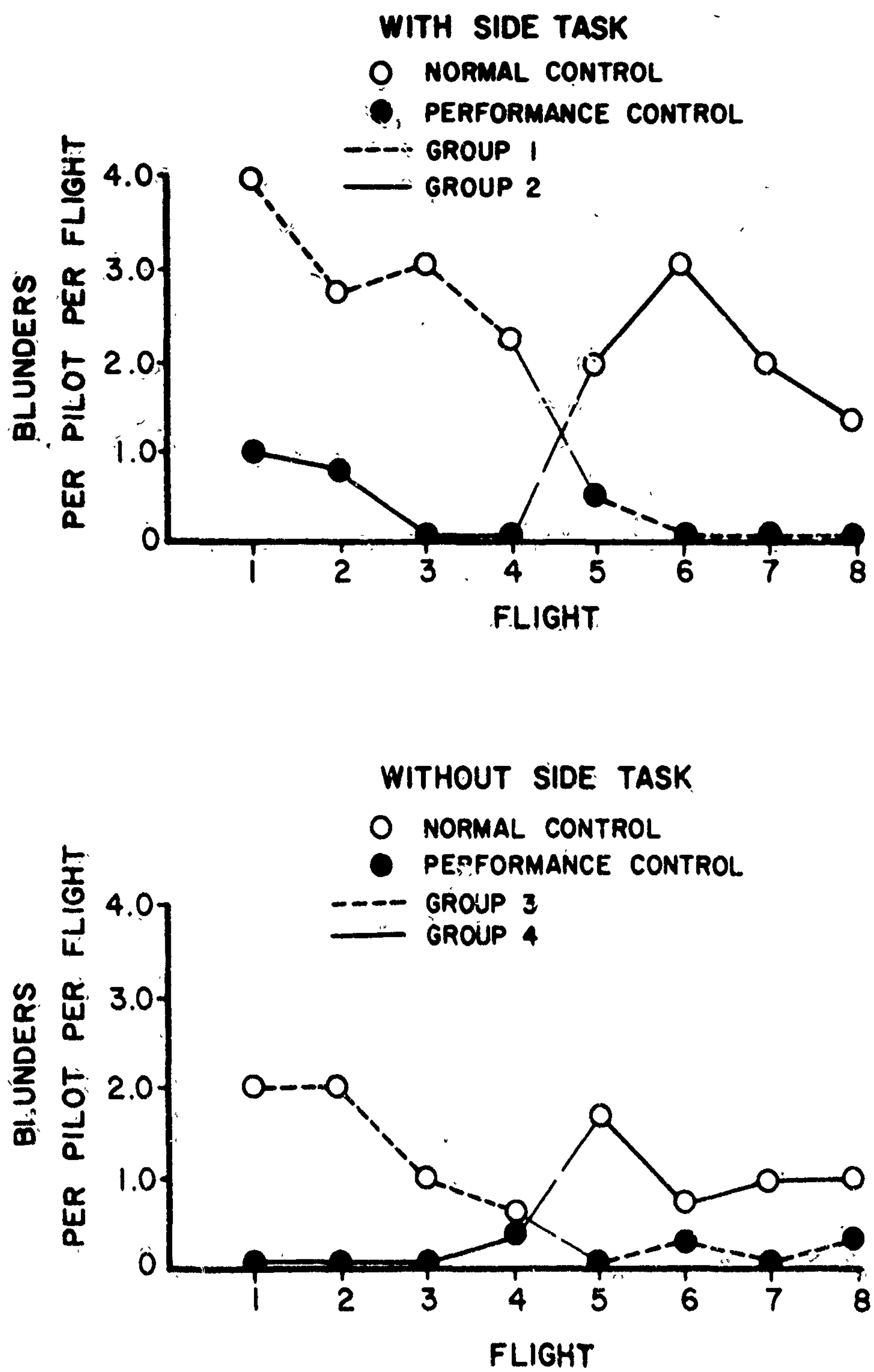


Figure 27. Comparison of effects of learning on procedural blunders with normal and performance controllers, with and without side-task loading. Longer dashed lines connect performances of groups of four pilots each.

Individual Differences. Figure 28, which shows the overall performance of each pilot, indicates a four-to-one range of residual attention capacity of different pilots within the same certification categories. Their performances correlate +.68 with their area navigation experience but -.22 with their total flight experience. The latter nonreliable correlation may be associated with the fact that, as flight experience increases, so does age.

Waypoint Storage Capacity Effects. The relatively small decrease in information processing rate for two-waypoint versus one-waypoint computer storage capacity, shown in Figure 29, is nonetheless a highly reliable effect with a ready explanation. With two waypoints available, pilots often became confused as to which was which. Because not all waypoint information was displayed simultaneously, a pilot had to keep the sequencing in his head or on his flight log. The alternating nature of the 1-2-1-2-1-2-1-2 sequence was harder to keep track of than the other sequences. The 1-2-3-4-5-6-7-8 sequence with eight-waypoint storage yielded the highest pilot attention for each control mode.

Primary Workload Effects. Side-task responses were summed according to the two flight regions, over and between waypoints. Information processing rates during flight in these regions with normal control and performance control are given in Table 7.

TABLE 7

Overall Information Processing Rates in Bits per Second for the Two Controllers in Two Flight Regions, Between Waypoints and Over Waypoints

Flight Region	Normal Control	Performance Control
Between Waypoints	0.672	0.858
Over Waypoints	0.569	0.766
Complete Flight	0.649	0.837

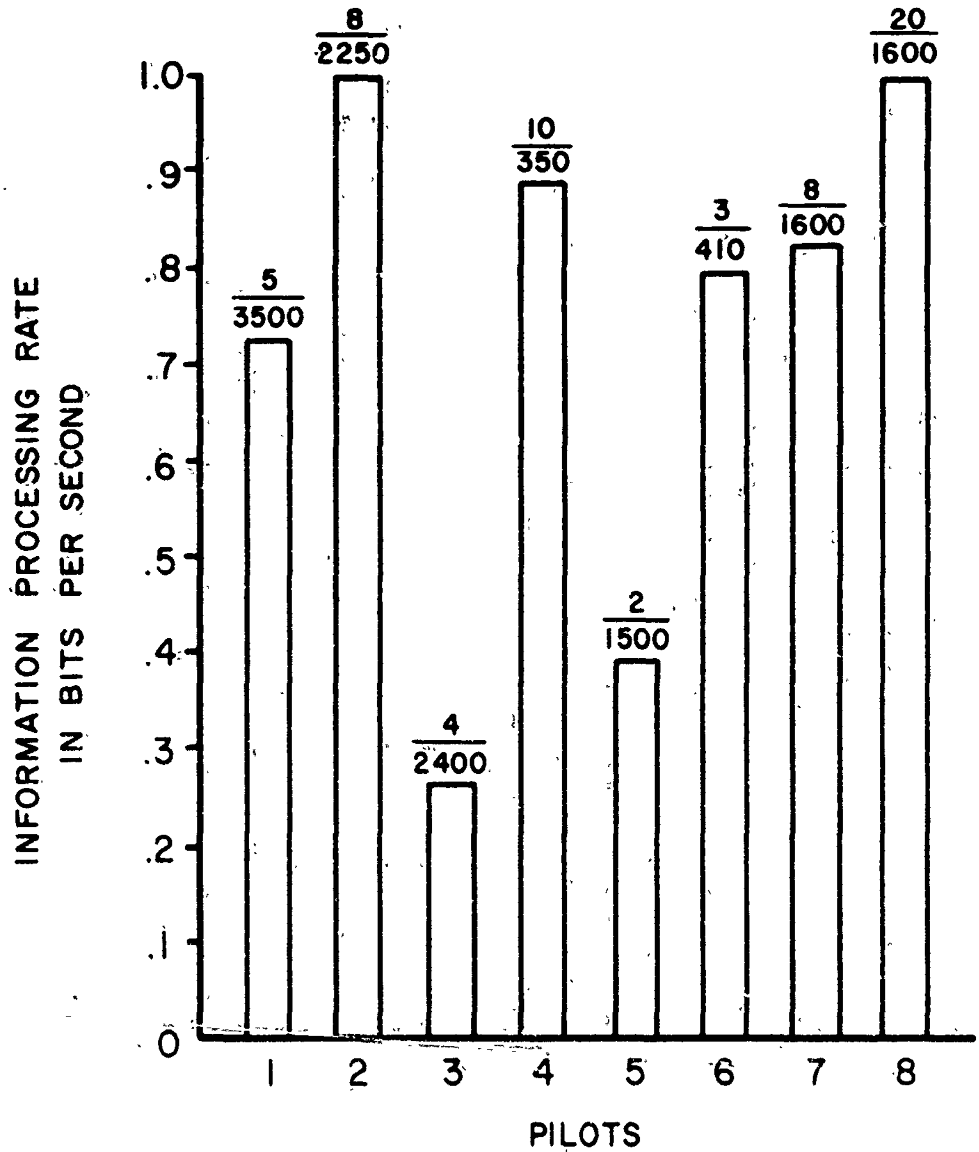


Figure 28. Overall side-task information processing rate for each pilot who received side-task loading. Numbers above bars indicate prior area navigation flight hours and total flight hours.

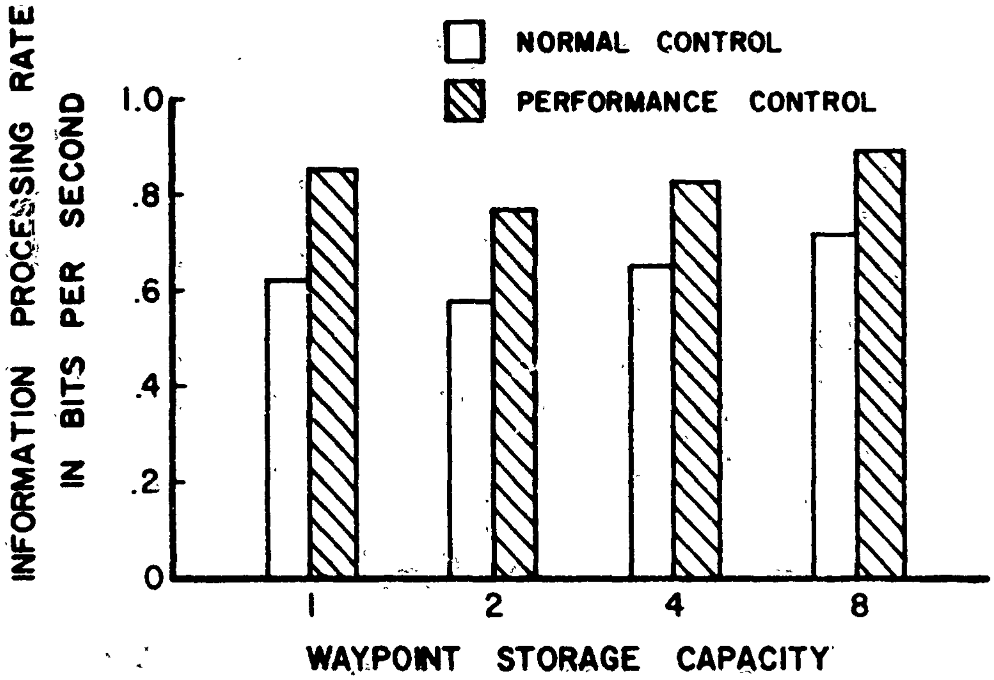


Figure 29. Side-task information processing rates for complete flights with normal flight control and flight performance control as a function of computer waypoint storage capacity.

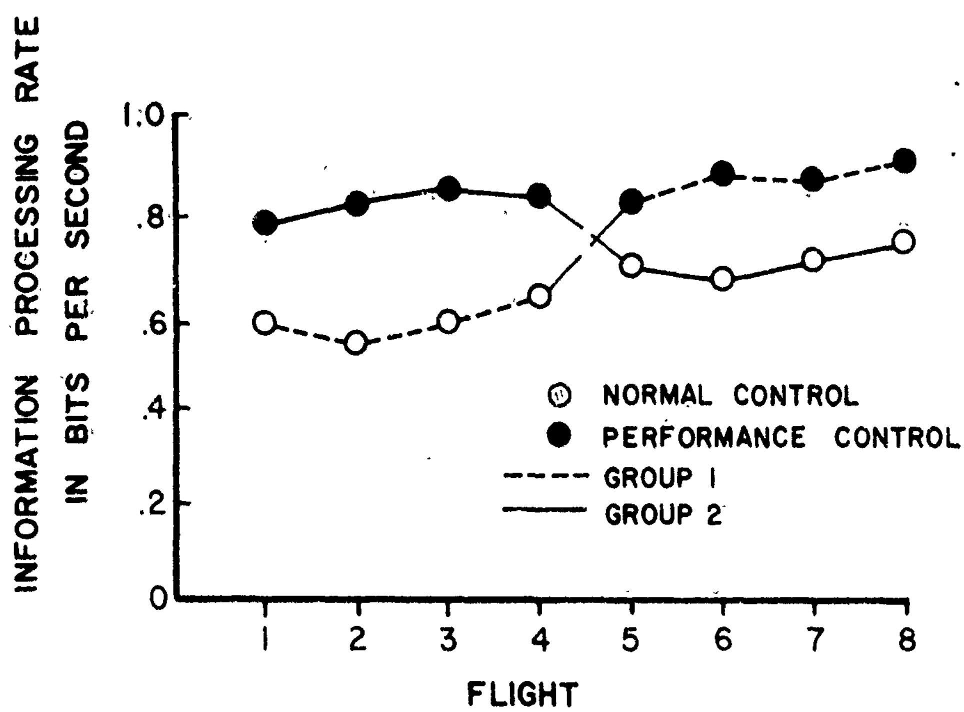


Figure 30. Side-task information processing rates with normal flight control and flight performance control as a function of practice. Longer dashed lines connect performances of groups of four pilots each.

The increased procedural and flight control demands while making course changes over waypoints were accompanied by a 15% reduction in information processing rate when flying with normal control and an 11% reduction with performance control, indicating reduced residual pilot attention during periods of elevated primary-task loading.

Learning Effects. Figure 30 presents residual pilot attention from trial to trial for the two pilot subgroups who flew a series of four flights with one or the other type of flight control system and then switched to the opposite type for four flights.

Although there was a statistically reliable increase in residual attention with practice on the experimental task, reflecting its previously mentioned correlation with prior area navigation experience, residual attention was far more strongly associated with flight control mode and individual pilot differences than with practice on the primary flight and navigation tasks. The composite 16% increase in residual attention over four flights with flight performance control, versus 32% for normal control, suggests that pilots would reach an asymptotic level of performance on area navigation procedures more quickly while using the performance control system.

DISCUSSION

The enhancement of human effectiveness in airborne system operation has three major facets, pilot selection and training and aircraft design. Tradeoffs can be made among all three. The tighter the selection, the less training pilots will require; the better the training, the looser admission may be. Although seldom thought of in the same way, it is also true that the human engineering of airplanes can reduce the need for either pilot selection or pilot training, as illustrated by the results of this experiment.

To allow quantitative tradeoffs among human abilities, training, and equipment design, a common metric is needed. The wide range of residual attention exhibited by similarly qualified pilots in this study reveals differences among them not attributable to training, while increases in residual attention with specific experience reflect effects of training. And the substantial increase in residual pilot attention not attributable either to pilot abilities or to specific training can only be attributed to engineering modifications of the airplane's control system and computer storage capacity.

The stress created by the side task was accompanied by a doubling of the frequency of pilot blunders, regardless of the manual control system in use. Despite the stressful effect of the elevated task loading and the four-to-one range of residual attention among professional pilots (approximately 0.25 to 1.00 bits per second), well-designed systems approached freedom from blunder proneness, indicating that it would not be unreasonable to require demonstration of a specified level of blunder-free residual attention by a group of properly qualified pilots for certification of a system.

The particular information processing side task described is only one of many that might be employed. It was used because it was simple to implement and score and because it was found to work during preliminary experimentation. A more complex cross-adaptive logic in which side-task stimulus presentation depends upon concurrent performance on the primary task has also been investigated (Damos, 1972; Damos and Roscoe, 1970). It also works, but not so well as the simple self-adaptive task just described.

The measurement of residual attention in a standardized manner under specified flight situations, whether in actual or simulated flight, offers a promising common basis for establishing the workload demand and blunder proneness of area navigation, vertical guidance, and other types of flight directing and control systems.

The maneuvering performance control system implemented in the GAT-2 effected significant improvements in flight accuracy and residual attention, and decreased blunders in navigational flight procedures. The success of the system parallels the positive results reported by Loschke, Barber, Jarvis, and Enevoldson (1972) for an attitude control system in a light twin-engine aircraft. These researchers have expressed a need for a reasonably economical development of light aircraft fly-by-wire systems before these systems are widely implemented in general aviation aircraft. In this direction, the Aviation Research Laboratory has recently finished electronic modifications and additions to the autopilot in its Beechcraft Twin Bonanza flying laboratory to allow maneuvering performance control through a dual sidearm stick controller mounted on the pilot's seat. The aircraft is certificated in the normal category with the performance control mode operative. Engineering evaluation of the performance controller in the aircraft shows the design approach used to be quite successful.

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APPENDIX A

INSTRUCTIONS TO PILOTS

Appendix A

INSTRUCTIONS TO PILOTS

For this experiment you will fly eight similar cross country flights in the GAT-2 (Figure 3). Each flight requires a total of approximately 35 minutes. All flights will be made under simulated IFR conditions using area navigation (RNAV) equipment for ground position reference and the three-axis sidearm stick for control. These two systems are described below.

AREA NAVIGATION

<u>Introduction</u>

One of the advantages of the area navigation system in the GAT-2 is the capability of selecting any given point (called a waypoint) within the range of a VORTAC station and flying to that point with direct guidance and a continuous display of aircraft position and heading with respect to that destination. Certain information must be provided to the RNAV computer to make this possible, including: (1) frequency of the VORTAC station to be used, (2) VOR radial along which the waypoint is situated, (3) distance of the waypoint from the VORTAC station, (4) selected track, and (5) instrument scale.

Figure A-1 shows the layout of a typical waypoint and track. For this case, assuming the VORTAC to be at Champaign, and the desired waypoint to be at Villa Grove, we have:

FREQ = 110.0
RAD = 148°
DIST = 11.7 nmi

The aircraft is shown flying outbound from the waypoint on a track of 203°. Note that as in the case of VOR navigation, the aircraft may have some relative heading with respect to the track due to wind.

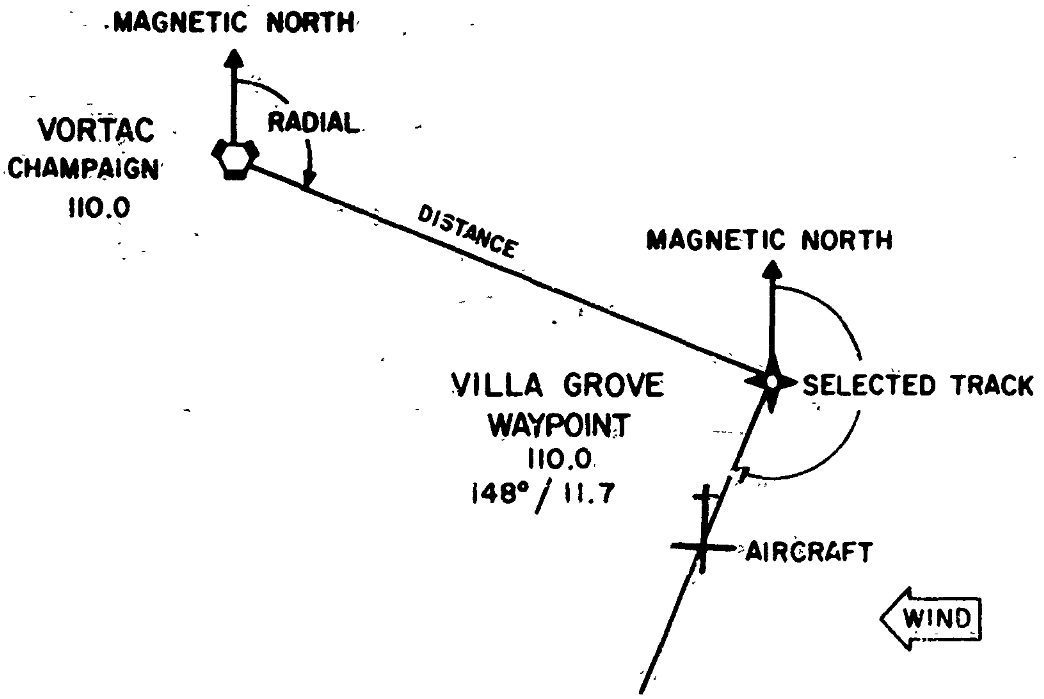

Figure A-1. Layout of RNAV waypoint and course.

RNAV Equipment

1. Symbolic-Pictorial Indicator. The RNAV equipment used for this experiment is based on the Butler SPI (Symbolic Pictorial Indicator) shown in Figures 4 and 8. The SPI is located in the instrument panel to the left of the RNAV control-display unit. A control is mounted on the SPI for selecting the desired track.

Two pointers in the SPI show the position of the waypoint with respect to the aircraft. The vertical needle indicates the position of the selected course or track (unless it is off scale). Hash marks on the face of the SPI give the perpendicular distance from the track to the airplane. Each mark represents 0.5 nautical mile. When the aircraft is on track the vertical needle will be centered. The horizontal needle indicates the distance along the track to the waypoint (unless off scale). Again, hash marks on the face of the SPI, each representing 0.5 nautical mile, assist in determining this distance. The intersection of the vertical and horizontal needles indicates the location of the selected waypoint.

A small symbolic aircraft, centered in the SPI, rotates 360° to indicate heading relative to the track setting. When flying on track, the aircraft symbol displays the wind correction angle needed to hold the track. When flying toward the track needle to center it, the aircraft symbol shows the intercept angle.

2. DME. An additional source of distance information is the DME indicator mounted in the lower left panel area. This instrument presents line-of-sight distance, that is, the shortest distance to the waypoint.

3. Control-Display Unit. The control-display unit (Figures 4 and 8) is designed to accept, store, and confirm waypoint information. To set a waypoint the pilot first assigns a number to the waypoint. He pushes the SET button, punches the waypoint number on the keyboard and then pushes the ENTER button. The system will then accept data for the SET waypoint. The frequency of the VORTAC is assigned by pushing FREQ, punching the frequency on the keyboard, and then pushing ENTER. The radial and distance inputs follow the same format, but using the RAD and DIST buttons respectively. To use a set waypoint, the pilot pushes the WPT IN USE button, selects the proper waypoint number on the keyboard, and pushes ENTER. The SPI then indicates information for the waypoint in use. Within the limits of storage capacity, a pilot may SET data for upcoming waypoints while flying to the WPT IN USE. Storage capacity will vary from flight to flight.

Waypoint data may be confirmed either during the input procedure or by means of the CONFIRM mode. As an input is punched on the keyboard, it is presented in one of several digital windows on the control panel. And as information is entered, the RNAV computer confirms the input data by redisplaying it in the same window. Thus, each time the ENTER button is pushed, the pilot should observe whether the displayed information is correct. If not, he should repeat the procedure for entering that information. A CONFIRM button is provided which allows the pilot to check data stored for any waypoint at any time. The SET window indicates the waypoint being confirmed. Note that no data can be input while the panel is in the CONFIRM mode.

SIDEARM CONTROLLER

Introduction

The sidearm stick controller mounted on the pilot's seat will be used for all eight flights. The controller can be rotated about all three axes, thereby combining the capabilities of both stick and rudder in one mechanism.

The controller operates by means of electrical signals to the flight controls. It is not connected by cables or rods, and is therefore called a "fly-by-wire" system. Standard trim controls are provided on the power pedestal, but they will not affect control forces. These forces are determined by springs in the mechanism. The trim wheels will affect aircraft trim in all attitudes, but due to the lack of aerodynamic force feedback it is recommended that trim be adjusted only to achieve straight and level flight. If, with the stick centered, there is a tendency to pitch, yaw, or roll, the proper trim wheel should be turned to the required setting. The system is very sensitive to trim inputs; therefore, adjustments in trim should be very small.

Control Modes

Two modes of aircraft control will be implemented through the sidearm stick for this experiment. These are described below:

1. Usual Aircraft Behavior. The GAT-2 dynamics in this mode are similar to a typical twin-engined light aircraft. The ailerons are controlled with a side-to-side motion as with a conventional stick. The stick motion for pitch control is unique in that the center of rotation of the mechanism is in the palm of the hand, rather than under the floor. Thus, pitch control is achieved with a twist of the wrist and requires no arm motion. The rudder is controlled by twisting the stick about its vertical axis rather than by pushing rudder pedals. Right rudder is commanded by twisting the stick clockwise, and vice-versa.

2. Fully Modified Behavior. In this mode, the GAT-2 pitch, roll, and yaw characteristics are modified.

(a) Pitch - the "fore-and-aft" motion of the stick controls rate of climb rather than pitch attitude. In turns, additional elevator deflection is automatically fed in to compensate for bank angle effects. When the stick is centered the altitude remains constant.

(b) Roll - the side-to-side motion of the stick controls bank angle rather than roll rate. When the stick is centered, the wings are level. Each lateral position of the stick corresponds to a bank angle which is maintained as long as the stick is held in that position.

(c) Yaw - coordination is provided automatically so that no rudder input is required for coordinated turns. Sideslip occurs only if called for by twisting the stick.

FLIGHT TASK

Each flight will begin with a takeoff, climb to altitude (3000 feet), and interception of the first leg of the area navigation course. A copy of the course is given in Figure A-2. During each flight, winds will be from 270° at 20K. Power controls should be left full forward throughout the flight.

Before takeoff you will be given your complete clearance and a simulated enroute chart (Figure A-2). As many waypoints as the system storage allows (this will vary) should be input before takeoff. The remainder can be input enroute.

The clearance for each waypoint includes the track on which you are to fly. The TRACK to each waypoint should be set while turning at the previous waypoint and should not be changed before the next waypoint is approached.

Each course segment is 12 nautical miles in length. At a convenient place between waypoints you should switch from the passed waypoint to the upcoming waypoint. As in airborne area navigation, small errors in the track setting will cause the courseline needle to jump to a new position when switching from one waypoint to another. Do not change the track selector. Instead make heading corrections to center the needle.

You may lead the turns, but not by more than one mile as shown on the SPI. No turns should be made at greater than standard rate.

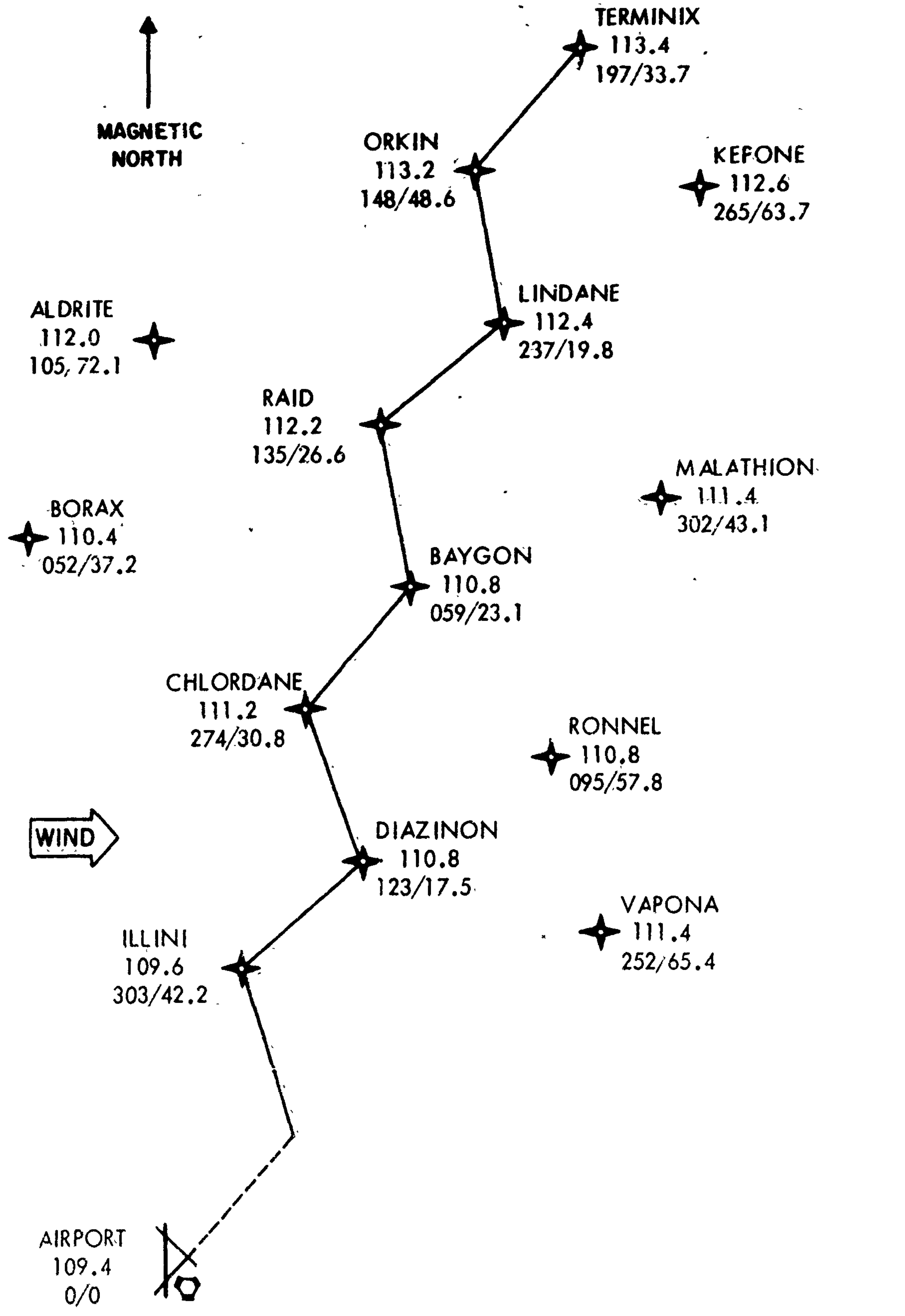

Figure A-2. Simulated enroute chart showing experimental area navigation course.

FLIGHT CLEARANCE

1000V is cleared to the Terminix waypoint

via radar vectors to the Illini 172° radial,
the 352° course to the Illini waypoint,
the 033° course to the Diazinon waypoint,
the 350° course to the Chlordane waypoint,
the 037° course to the Baygon waypoint,
the 356° course to the Raid waypoint,
the 044° course to the Lindane waypoint,
the 357° course to the Orkin waypoint,
the 040° course to the Terminix waypoint,
climb to and maintain 3000.
Contact Tower 120.5 when ready for takeoff.

TAKEOFF CLEARANCE

1000V is cleared for takeoff. Maintain runway heading until interception of the Illini 172° radial.

INFORMATION PROCESSING SIDE TASK

[For pilots 1-8 only]

The CAT-2 panel includes a linear array of ten white lights just above the instruments and a response keyboard mounted to the left of the power pedestal. During your flights lights 1 through 8 will come on in random order. If time permits, you should respond as quickly as possible by pushing the corresponding keyboard number. Your primary task is to fly each course as accurately as possible. You should respond to lights only if you are sure that the extra workload will not affect flight accuracy; nevertheless, a horn will sound several seconds after a light signal if you fail to respond to it. This is to remind you to try to pay more attention to the keyboard responses.

APPENDIX B

MEANS AND STANDARD DEVIATIONS OF CROSSTRACK AND ALTITUDE ERRORS FOR EACH FLIGHT, WITH AND WITHOUT SIDE-TASK LOADING

TABLE B-1

Mean Crosstrack Errors for Each Flight with Side-Task Loading

Pilot	Trial 1	2	3	4	5	6	7	8
	Normal Control				Performance Control			
1	.60	.22	.25	.26	.19	.01	.06	.05
2	.12	.54	.18	.09	.18	.12	.11	.07
3	.08	.11	.08	.09	.05	.05	.01	.02
4	.41	.08	.10	-.10	.14	.12	.08	.08
	Performance Control				Normal Control			
5	.35	.18	.09	.21	.44	.48	.50	.59
6	-.26	-.01	.13	.20	.21	.10	.20	.07
7	.44	.37	.16	.15	.47	.31	.16	.19
8	.10	.16	.09	-.01	.23	.03	.16	-.02

TABLE B-2

Standard Deviations of Crosstrack Errors for Each Flight with Side-Task Loading

Pilot	Trial 1	2	3	4	5	6	7	8
	Normal Control				Performance Control			
1	.94	.89	.88	.48	.28	.18	.17	.20
2	.84	.50	.32	.23	.29	.18	.25	.24
3	.24	.11	.13	.21	.13	.15	.14	.11
4	.50	.56	.20	.58	.26	.12	.15	.16
	Performance Control				Normal Control			
5	.38	.20	.36	.25	.31	.42	.36	.44
6	.71	.49	.32	.28	.38	.32	.24	.15
7	.61	.26	.21	.19	.50	.43	.14	.14
8	.23	.23	.17	.19	.42	.15	.25	.18

TABLE B-3

Mean Altitude Errors for Each Flight with Side-Task Loading

Pilot	Trial 1	2	3	4	5	6	7	8
	Normal Control				Performance Control			
1	100	60	4	-50	2	5	1	1
2	-92	30	-80	33	4	9	7	-7
3	50	33	-14	76	13	14	12	13
4	345	84	-5	10	4	-2	1	-2
	Performance Control				Normal Control			
5	1	3	4	5	237	-9	56	-37
6	6	5	4	6	61	24	37	-8
7	3	2	1	7	87	-16	29	-7
8	7	-1	0	-5	50	30	17	4

TABLE B-4

Standard Deviations of Altitude Errors for Each Flight with Side-Task Loading

Pilot	Trial							
	1	2	3	4	5	6	7	8
	Normal Control				Performance Control			
1	163	145	116	88	28	24	32	34
2	70	73	58	64	30	20	21	19
3	85	72	51	62	7	7	8	6
4	279	221	40	40	40	32	35	23
	Performance Control				Normal Control			
5	46	31	36	28	327	112	171	100
6	25	21	21	18	39	135	33	38
7	29	27	25	16	108	75	76	74
8	17	34	30	25	65	47	59	56

TABLE B-5

Mean Crosstrack Errors for Each Flight Without Side-Task Loading

Pilot	Trial 1	2	3	4	5	6	7	8
	Normal Control				Performance Control			
9	.38	.09	.25	.04	.00	-.01	-.03	.00
10	.15	.02	.08	.04	.02	.04	.03	.04
11	.06	.00	.02	.11	.03	.09	.06	-.02
12	.11	.19	.09	.06	.02	.00	.02	-.01
	Performance Control				Normal Control			
13	-.08	-.03	-.01	.07	.10	.23	-.04	-.01
14	.06	.07	.05	.06	.09	.02	.05	.25
15	.04	.03	.06	.05	.15	.14	.11	.20
16	.12	.09	.10	.11	.12	.10	.12	.18

TABLE B-6

Standard Deviations of Crosstrack Errors for Each Flight Without Side-Task Loading

Pilot	Trial 1	2	3	4	5	6	7	8
	Normal Control				Performance Control			
9	.88	.17	.30	.25	.09	.10	.12	.09
10	.31	.20	.10	.10	.11	.15	.13	.09
11	.25	.30	.33	.30	.07	.10	.08	.11
12	.25	.58	.30	.16	.08	.07	.05	.06
	Performance Control				Normal Control			
13	.19	.14	.26	.13	.23	.26	.33	.31
14	.15	.14	.10	.09	.18	.16	.09	.48
15	.14	.08	.07	.16	.24	.35	.34	.22
16	.13	.08	.14	.07	.16	.11	.20	.13

TABLE B-7

Mean Altitude Errors for Each Flight Without Side-Task Loading

Pilot	Trial 1	2	3	4	5	6	7	8
	Normal Control				Performance Control			
9	186	10	-22	8	-8	-9	0	-3
10	91	72	32	-14	-2	0	6	2
11	5	-10	-26	10	1	3	0	-5
12	28	130	30	8	3	1	4	3
	Performance Control				Normal Control			
13	12	3	3	6	65	57	26	37
14	-1	-5	-1	-2	-6	-20	49	71
15	-3	2	2	4	26	-5	53	63
16	-4	-4	-2	-4	-25	9	28	6

TABLE B-8

Standard Deviations of Altitude Errors for Each Flight Without Side-Task Loading

Pilot	Trial 1	2	3	4	5	6	7	8
	Normal Control				Performance Control			
9	187	79	66	84	10	12	15	18
10	83	99	64	43	16	23	14	17
11	43	50	42	59	9	10	18	7
12	233	99	66	63	12	14	14	13
	Performance Control				Normal Control			
13	6	19	21	18	66	57	56	60
14	30	20	21	19	120	81	72	129
15	19	11	10	15	75	85	96	111
16	14	15	15	16	40	30	54	50

APPENDIX C

PROCEDURAL ERRORS FOR EACH FLIGHT, WITH AND WITHOUT SIDE-TASK LOADING

TABLE C-1

Total Procedural Errors for Each Flight with Side-Task Loading

Pilot	Trial 1	2	3	4	5	6	7	8
	Normal Control				Performance Control			
1	11	1	4	4	0	0	0	0
2	4	4	4	0	1	0	0	0
3	0	2	0	1	0	0	0	0
4	1	4	4	4	1	0	0	0
	Performance Control				Normal Control			
5	2	1	0	0	3	5	5	4
6	1	1	0	0	1	5	0	1
7	1	1	0	0	3	4	1	0
8	0	0	0	0	1	0	2	0

TABLE C-2

Total Procedural Errors for Each Flight Without Side-Task Loading

Pilot	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 6	Trial 7	Trial 8
	Normal Control				Performance Conrrol			
9	6	1	1	1	0	0	0	0
10	0	2	0	0	0	1	0	1
11	0	0	0	0	0	0	0	0
12	2	5	3	1	0	0	0	0
	Performance Control				Normal Control			
13	0	0	0	0	0	0	1	1
14	0	0	0	0	1	1	1	2
15	0	0	0	1	4	2	1	0
16	0	0	0	1	2	0	1	1

APPENDIX D

SIDE-TASK RESPONSES FOR EACH FLIGHT OF FIRST REPLICATION

TABLE D-1

Total Side-Task Responses for Each Flight of First Replication

Pilot	Trial 1	2	3	4	5	6	7	8
	Normal Control				Performance Control			
1	317	406	237	372	488	455	452	442
2	454	455	512	554	597	649	586	748
3	64	90	156	107	147	187	182	189
4	427	340	365	365	604	661	500	635
	Performance Control				Normal Control			
5	214	291	240	228	201	165	216	178
6	390	473	510	567	448	369	443	347
7	500	466	534	506	363	411	379	480
8	629	587	602	558	529	539	532	663

TABLE D-2

Side-Task Responses During Straight Flight for Each Trial of First Replication

Pilot	Trial 1	2	3	4	5	6	7	8
	Normal Control				Performance Control			
1	269	352	191	273	397	372	353	396
2	372	379	405	434	458	510	455	580
3	50	66	119	82	114	145	140	143
4	360	287	296	276	462	529	391	499
	Performance Control				Normal Control			
5	155	237	203	156	151	133	172	148
6	302	366	393	456	348	296	365	259
7	393	379	431	399	299	334	313	367
8	504	483	465	445	414	445	392	530

TABLE D-3

Side-Task Responses While Turning for Each Flight of First Relication

Pilot	Trial 1	2	3	4	5	6	7	8
	Normal Control				Performance Control			
1	48	54	46	99	91	83	99	46
2	82	76	107	120	139	139	131	168
3	14	24	37	25	33	42	42	46
4	67	53	69	89	142	132	109	136
	Performance Control				Normal Control			
5	59	54	37	72	50	32	44	30
6	88	107	117	111	100	73	78	88
7	107	87	103	107	64	77	66	113
8	125	104	137	113	115	94	140	133

APPENDIX E

ANALYSIS OF VARIANCE SUMMARY

TABLE E-1

Analysis of Variance for RMS Altitude Errors

Source	df	MS	F	Prob.
Between Subjects				
Side Task (ST)	1	10029.	2.207	0.160
Subjects (S/ST)	14	4544.		
Within Subjects				
Control Mode (C)	1	221528.	6[illegible].547	<0.001
ST X C	1	1838.	0.552	0.470
C X S/ST	14	3329.		
Trial (T)	3	12518.	6.360	0.001
ST X T	3	2293.	1.165	0.334
T X S/ST	42	1968.		
C X T	3	11257.	6.156	0.001
ST X C X T	3	1762.	0.964	0.419
C X T X S/ST	42	1829.		

TABLE E-2

Analysis of Variance for Log of RMS Altitude Errors

Source	df	MS	F	Prob.
Between Subjects				
Side Task (ST)	1	0.6253	6.160	0.026
Subjects (S/ST)	14	0.1015		
Within Subjects				
Control Mode (C)	1	13.5045	379.696	<0.001
ST X C	1	0.1473	4.142	0.061
C X S/ST	14	0.0356		
Trial (T)	3	0.1334	6.150	0.001
ST X T	3	0.0318	1.465	0.238
T X S/ST	42	0.0217		
C X T	3	0.0888	4.569	0.007
ST X C X T	3	0.0075	0.384	0.765
C X T X S/ST	42	0.0194		

TABLE E-3

Analysis of Variance for RMS Crosstrack Errors

Source	df	MS	F	Prob.
Between Subjects				
Side Task (ST)	1	0.9402	13.764	0.002
Subjects (S/ST)	14	0.0683		
Within Subjects				
Control Mode (C)	1	0.9818	13.286	0.003
ST X C	1	0.0003	0.004	0.952
C X S/ST	14	0.0739		
Trial (T)	3	0.1183	7.697	<0.001
ST X T	3	0.0586	3.814	0.017
T X S/ST	42	0.0154		
C X T	3	0.0083	0.544	0.655
ST X C X T	3	0.0028	0.182	0.908
C X T X S/ST	42	0.0152		

TABLE E-[illegible]

Analysis of Variance for Log of RMS Crosstrack Errors

Source	df	MS	F	Prob.
Between Subjects				
Side Task (ST)	1	2.1923	19.472	<0.001
Subjects (S/ST)	14	0.1126		
Within Subjects				
Control Mode (C)	1	2.2812	22.922	<0.001
ST X C	1	0.2266	2.277	0.154
C X S/ST	14	0.0995		
Trial (T)	3	0.1493	7.098	<0.001
ST X T	3	0.0596	2.835	0.050
T X S/ST	42	0.0210		
C X T	3	0.0040	0.182	0.908
ST X C X T	3	0.0027	0.125	0.945
C X T X S/ST	42	0.0218		

TABLE E-5

Analysis of Variance for Information Processing Rates

Source	df	MS	F	Prob.
Between Subjects				
Subjects (S)	7	0.6503		
Within Subjects				
Control Mode (C)	1	0.5629	22.244	0.002
C X S	7	0.0253		
Waypoint Storage (W)	3	0.0472	11.069	<0.001
W X S	21	0.0043		
C X W	3	0.0042	0.572	0.640
C X W X S	21	0.0073		